Less Mass, More Science

How cavity-enhanced spectroscopy can improve science returns and decrease cost for in-situ planetary measurements

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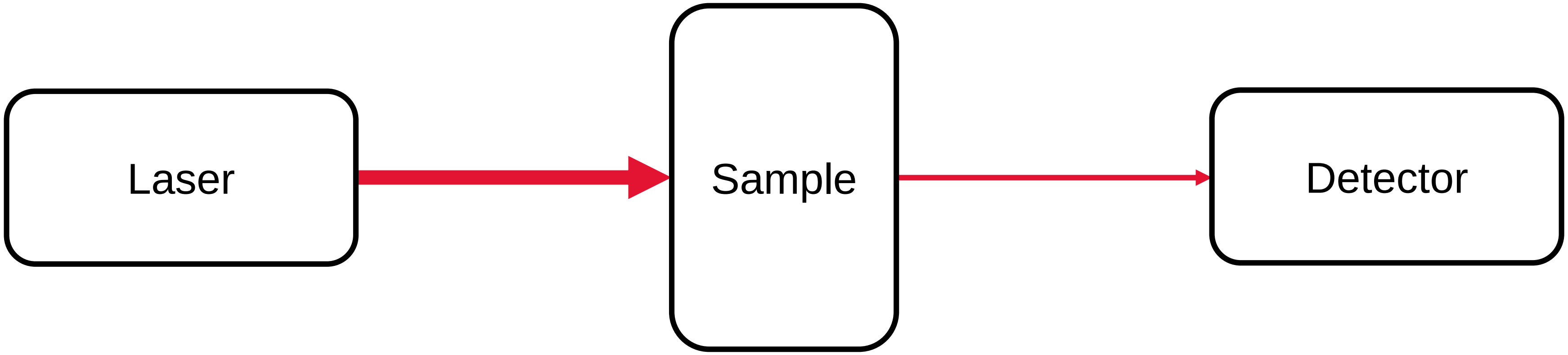
- What is Tunable Laser Spectroscopy?
- What can we measure with TLS?
- What goes into making a TLS for planetary missions?
- How can we improve, and what could we do then?

- What is cavity-enhanced spectroscopy?
- What are the design tradeoffs?
- What is unique about our design?
- How well does the spectrometer perform?
- What can we improve in the future?

Tunable Laser Spectroscopy Overview

What is TLS?

Tunable Laser Spectroscopy (TLS) uses the attenuation of narrow-band laser light to achieve **sensitive**, **selective** detection of molecules over a **wide range of pressures**.



What can we measure?

We can measure molecules that are:

- Between 2 and 12 atoms in size (more if rigid, like benzene)
- Present at parts-per-billion volume or greater (ppb wt for solids)
- In the gas phase, or can be vaporized

TLS can:

- Easily distinguish species of similar mass – e.g. $C^{13}O^{16}O^{16}$ from $C^{12}O^{16}O^{17}$ and $C^{12}H_4$ from O^{16}
- Provide highly localized measurements

What are the real-world applications?

Earth Science:

- Observe water transport through tropopause / stratosphere via isotopic measurements
- Measure methane / CO_2 isotope fluxes to localize and quantify sources and sinks
- Monitor concentrations of reactive species (halogen compounds, NO, OH) and ozone
- Monitor emission of volcanic gases

What are the real-world applications?

Planetary Science:

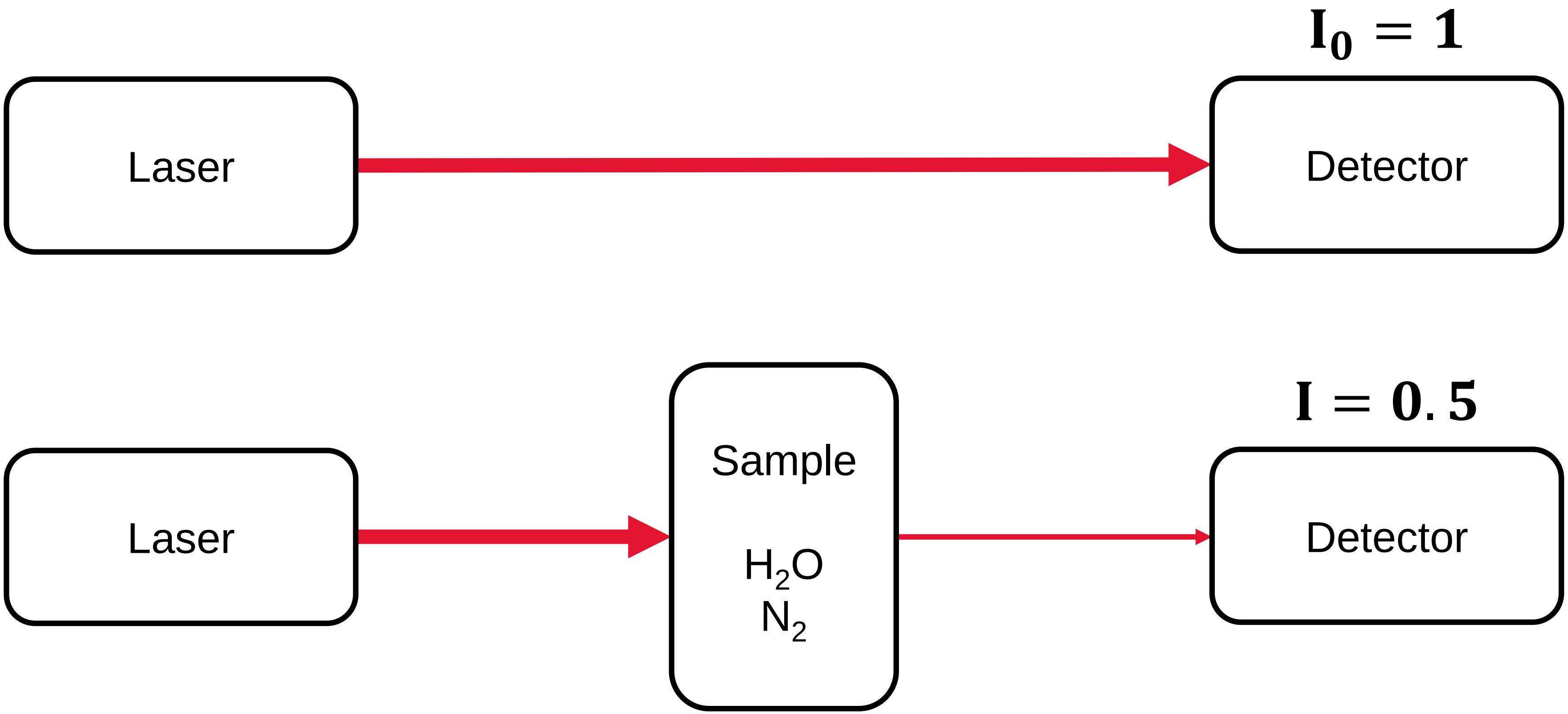
- Isotope ratio studies of various compounds – CO_2, H_2O, CH_4, PH_3, NH_3, SO_2 – as tracers of solar system formation, geological and atmospheric processes of each body
- Localized mixing ratios for atmospheric layers or near sites of geological or atmospheric activity
- Detection of trace quantities of biologically-relevant gases in atmosphere or processed samples

What are the real-world applications?

Miscellaneous:

- Laboratory measurements in support of astronomy
- Observations of combustion chemistry / physics
- Breath analysis for medical diagnostics
- Safety monitoring for mining, drilling, and manufacturing industries

What is TLS?



$$\mathbf{T = \frac{I}{I_0} = 50\%} \qquad \mathbf{A = \log_{10}\frac{I_0}{I} = 0.3}$$

What is TLS?

Absorption cross-section (cm^2)

$$\mathbf{A = \sigma \rho l}$$

Path length (cm)

Volume density (cm^{-3})

Absorption coefficient (cm^{-1})

$$\boldsymbol{\alpha \equiv \sigma \rho}$$

Noise-equivalent absorption (NEA):

Absorption signal equal to one standard deviation of the absorption measurement.

- Detector and shot noise
- Laser wavelength and intensity fluctuations
- Mechanical and thermal perturbations
- Etalons / fringing

What is TLS?

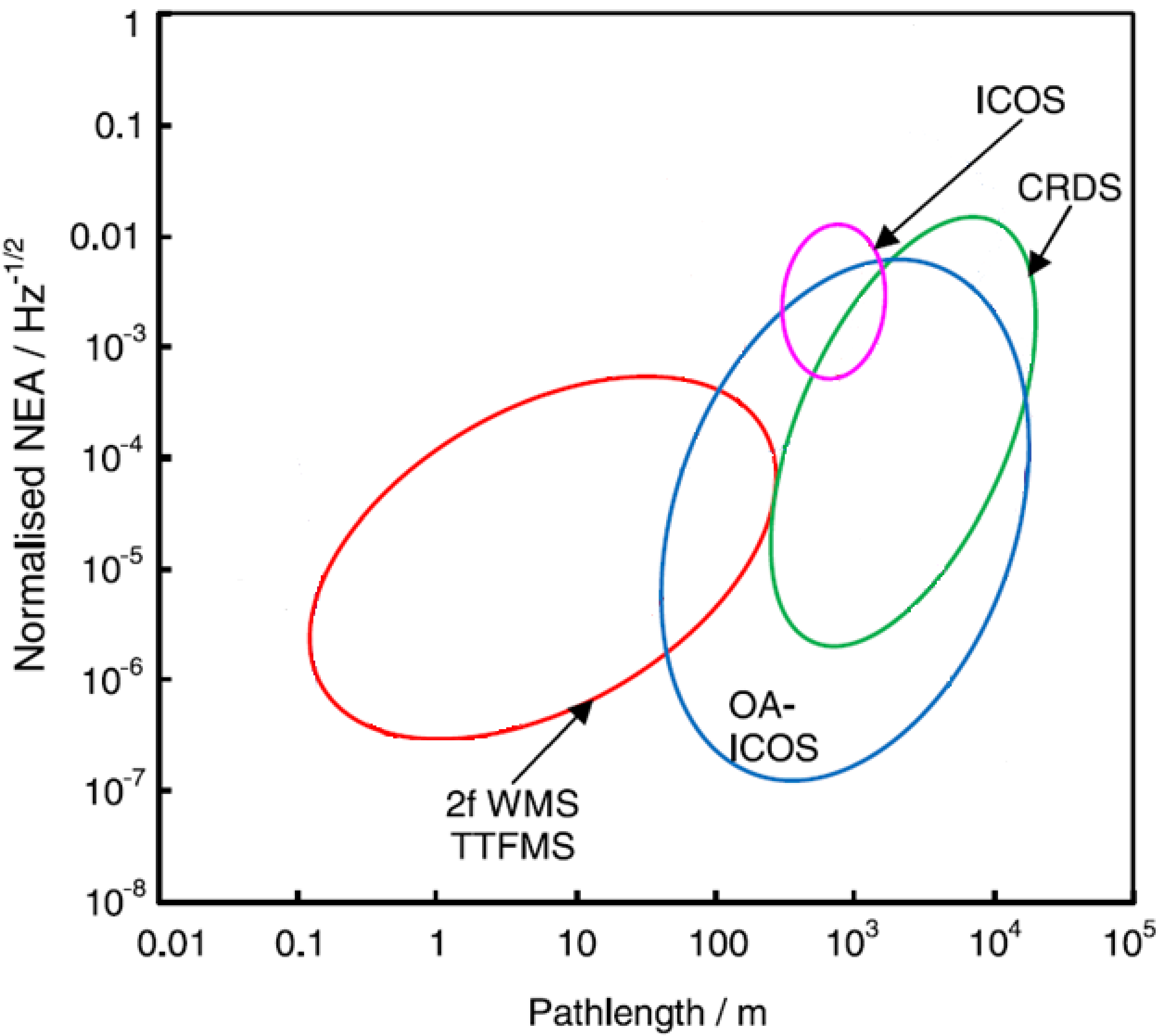


Figure adapted from J Hodgkinson and RP Tatam 2013 Meas. Sci. Technol. 24 012004

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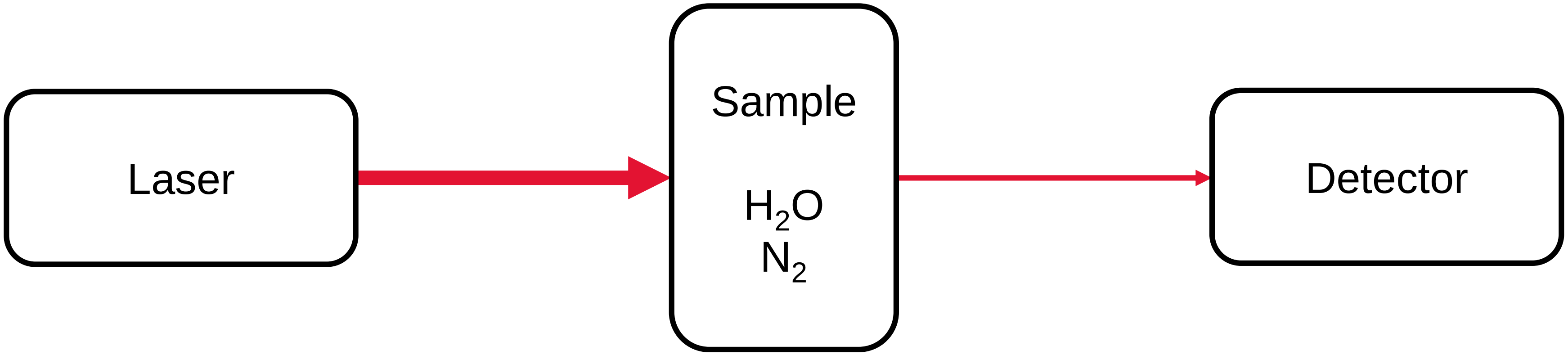
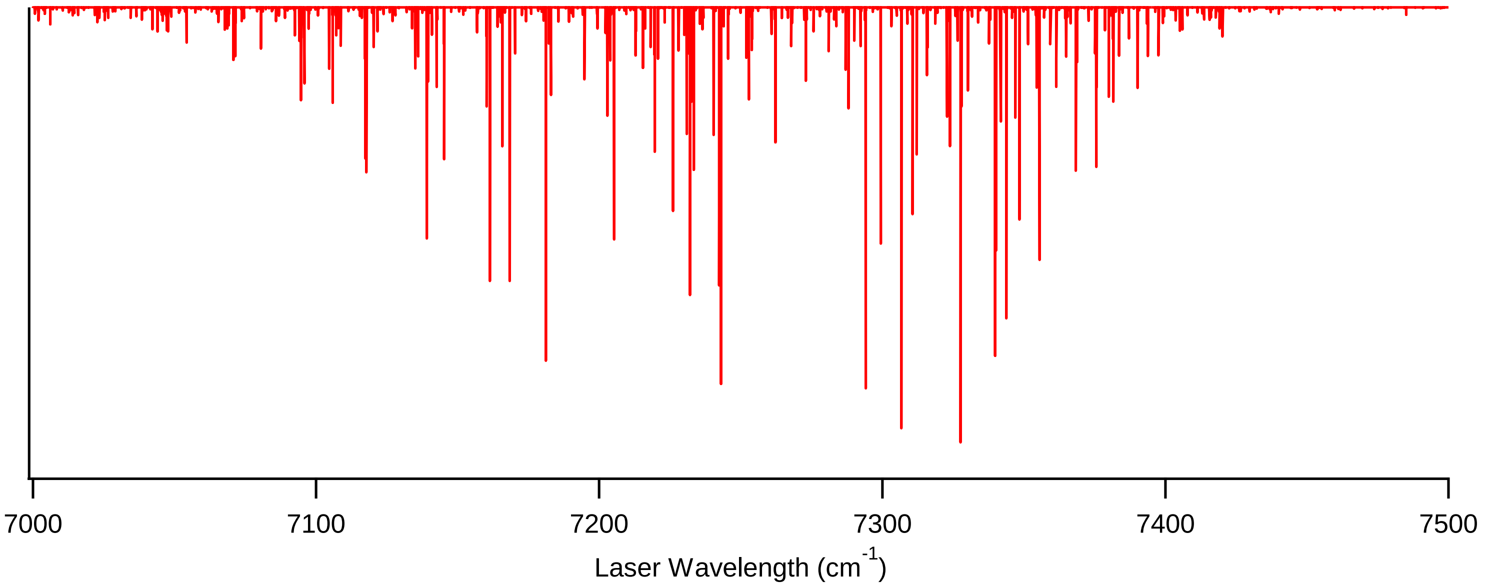
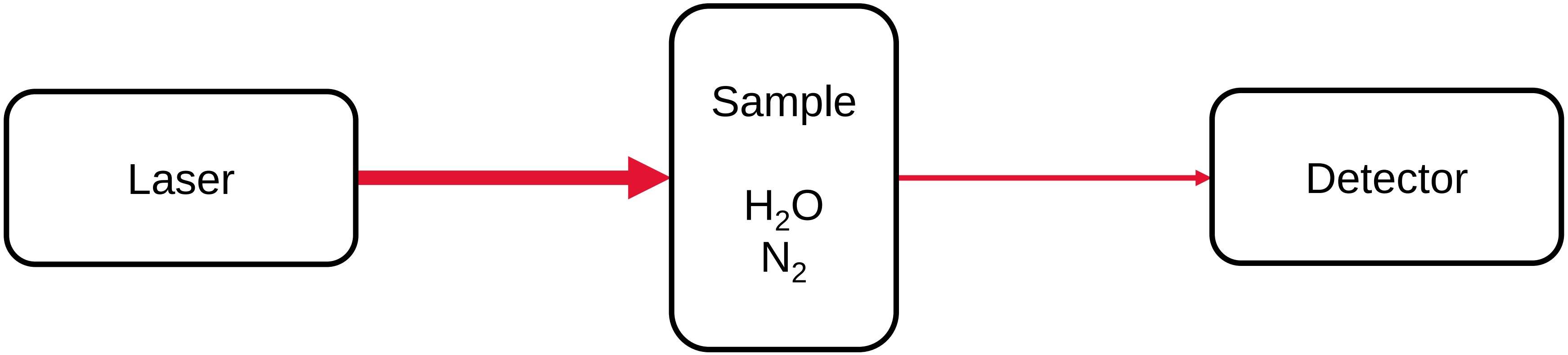
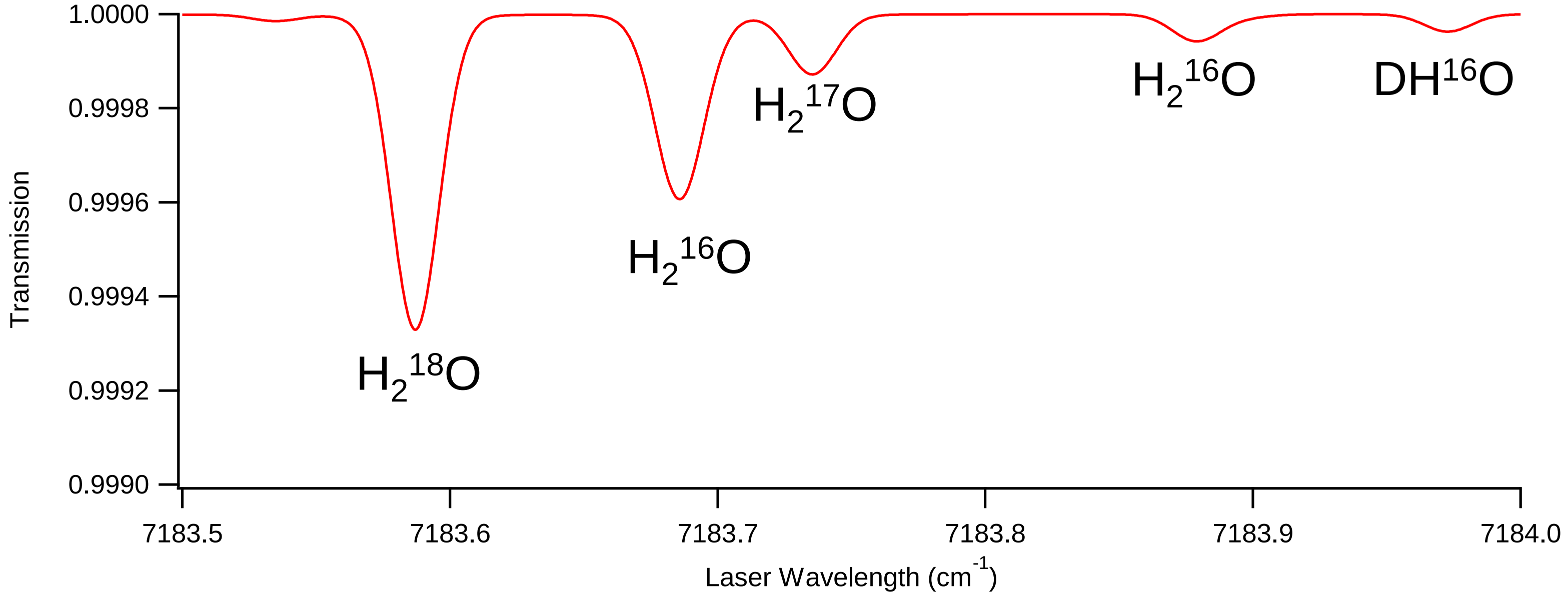




Data from HITRAN

What is TLS?





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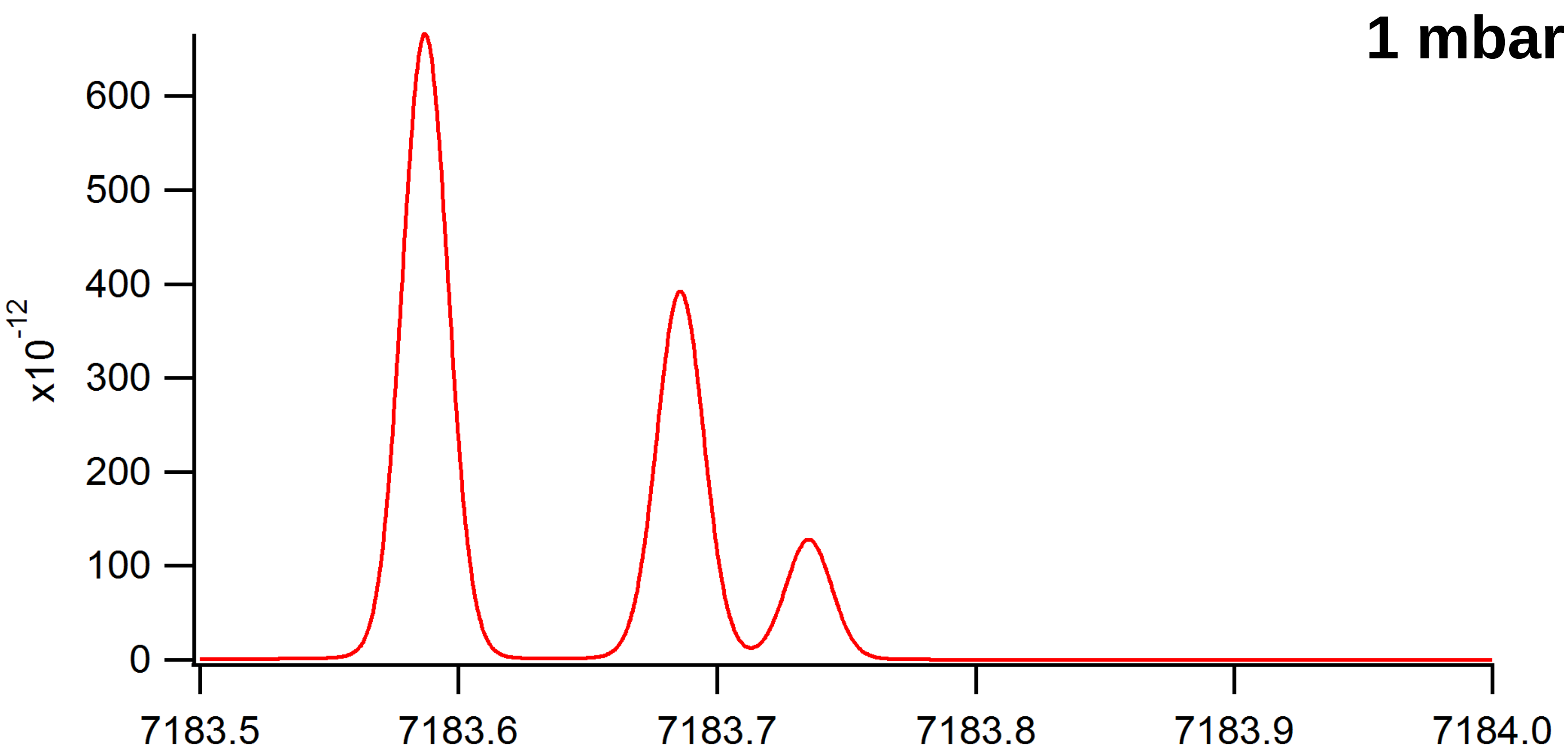

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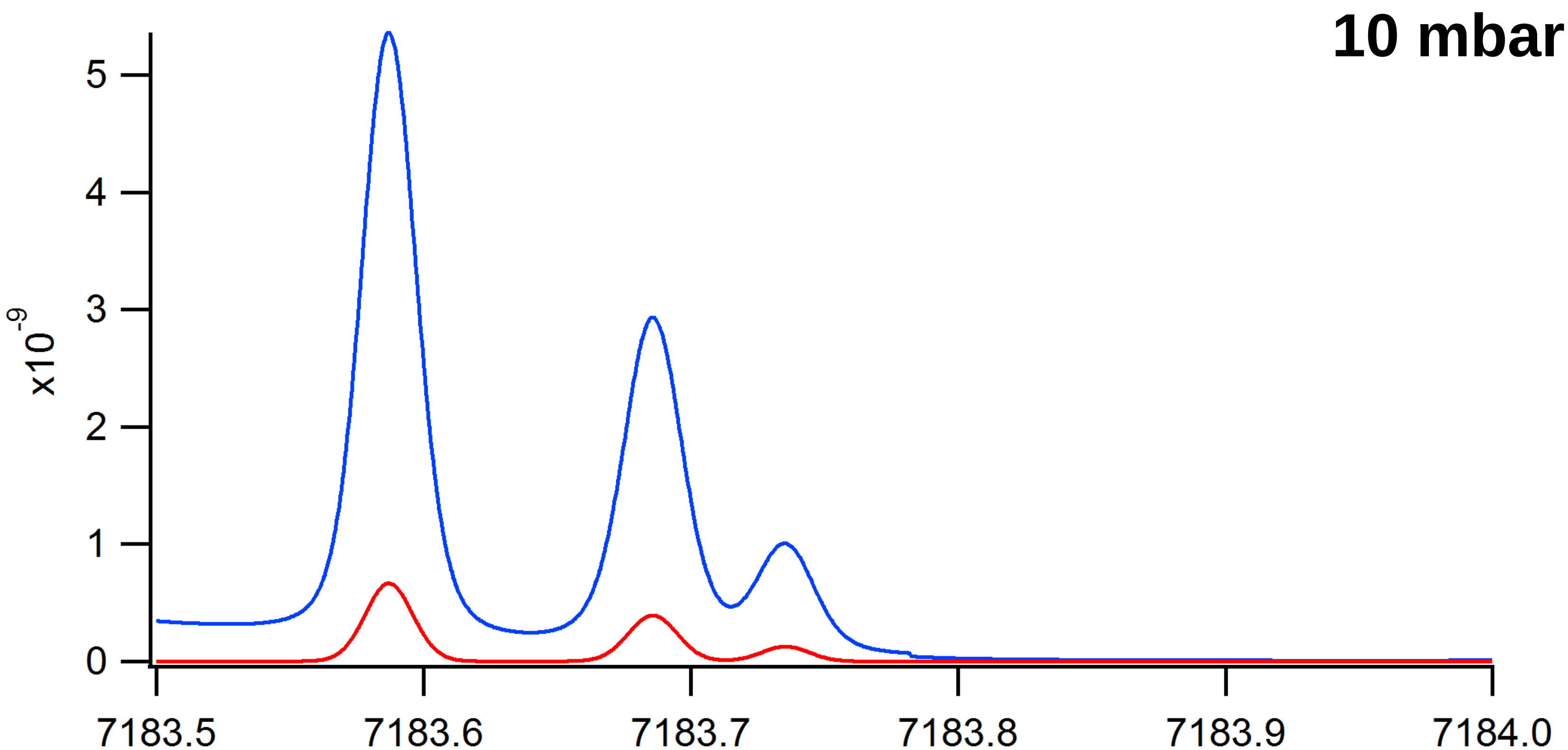

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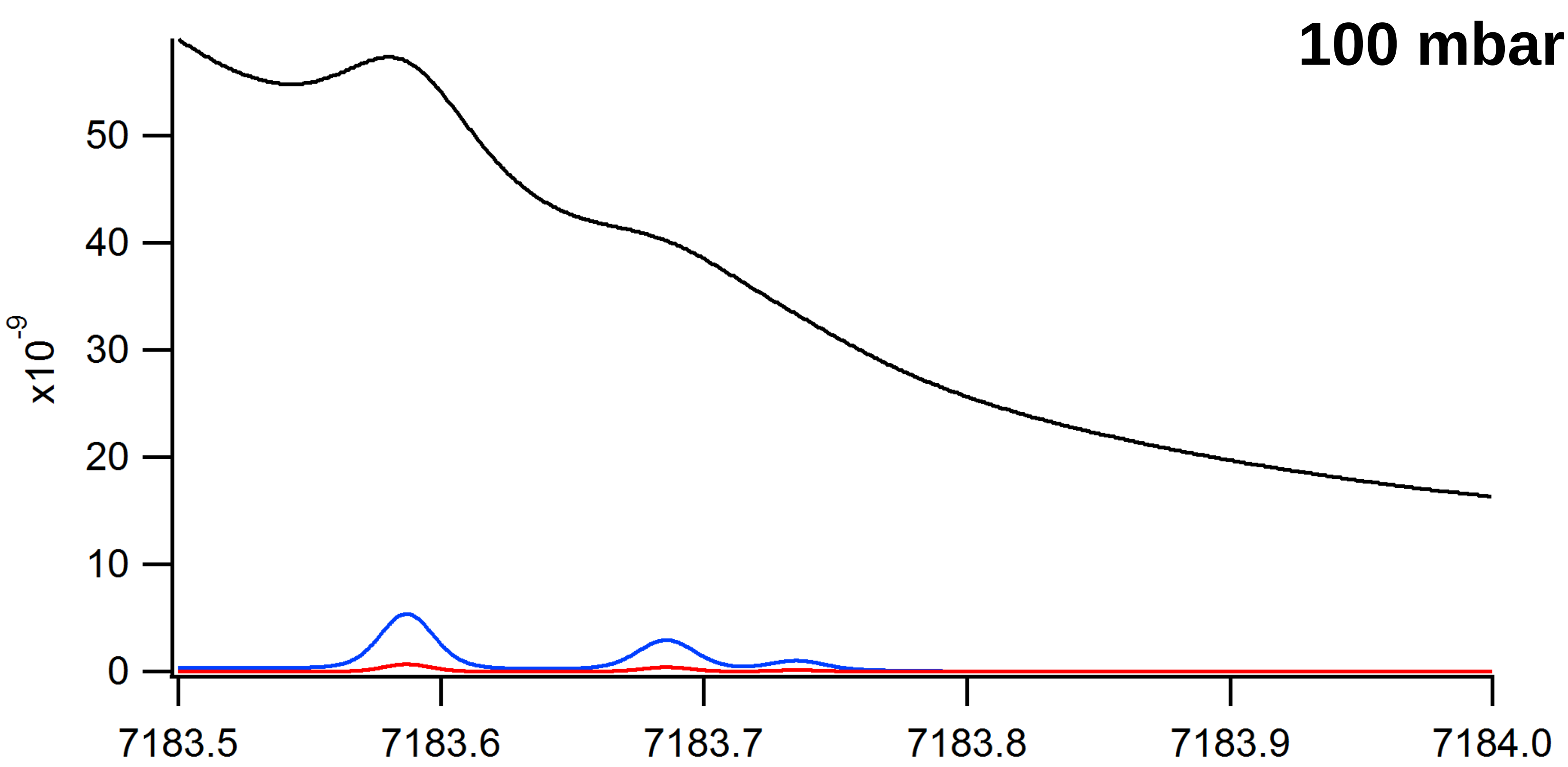
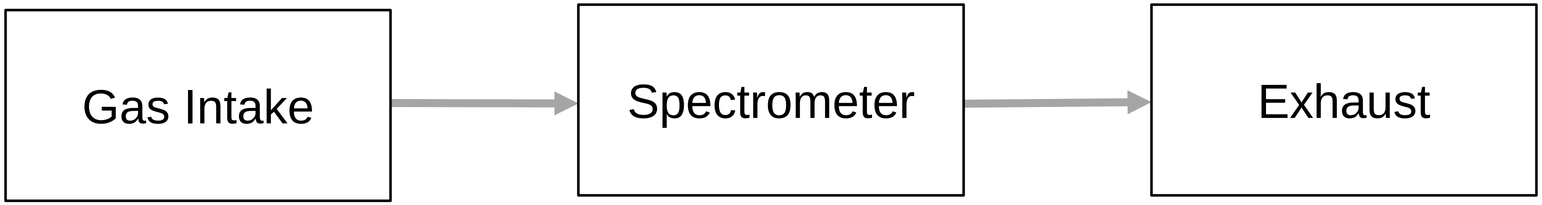


Data from HITRAN

What does a TLS system look like?



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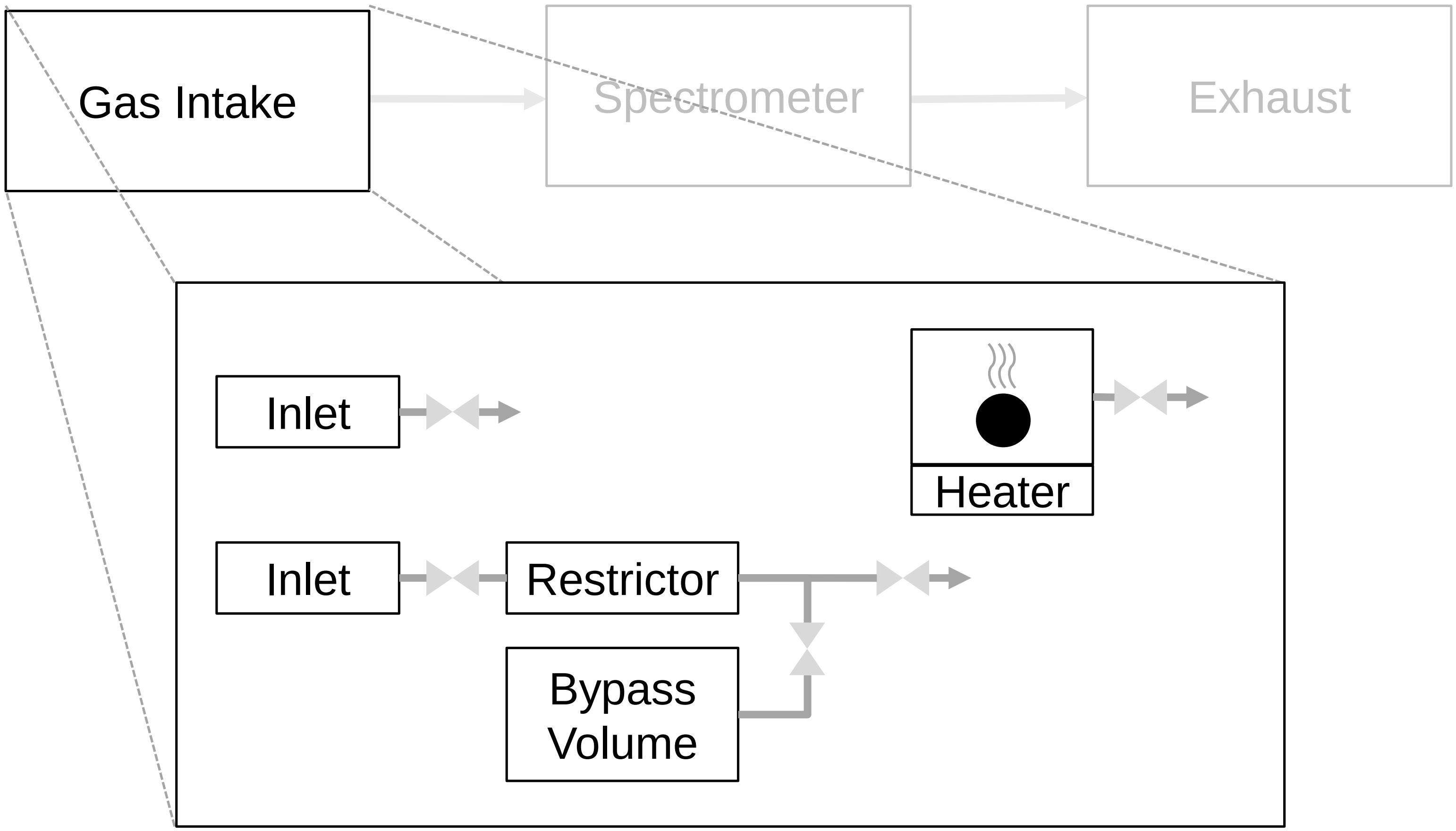

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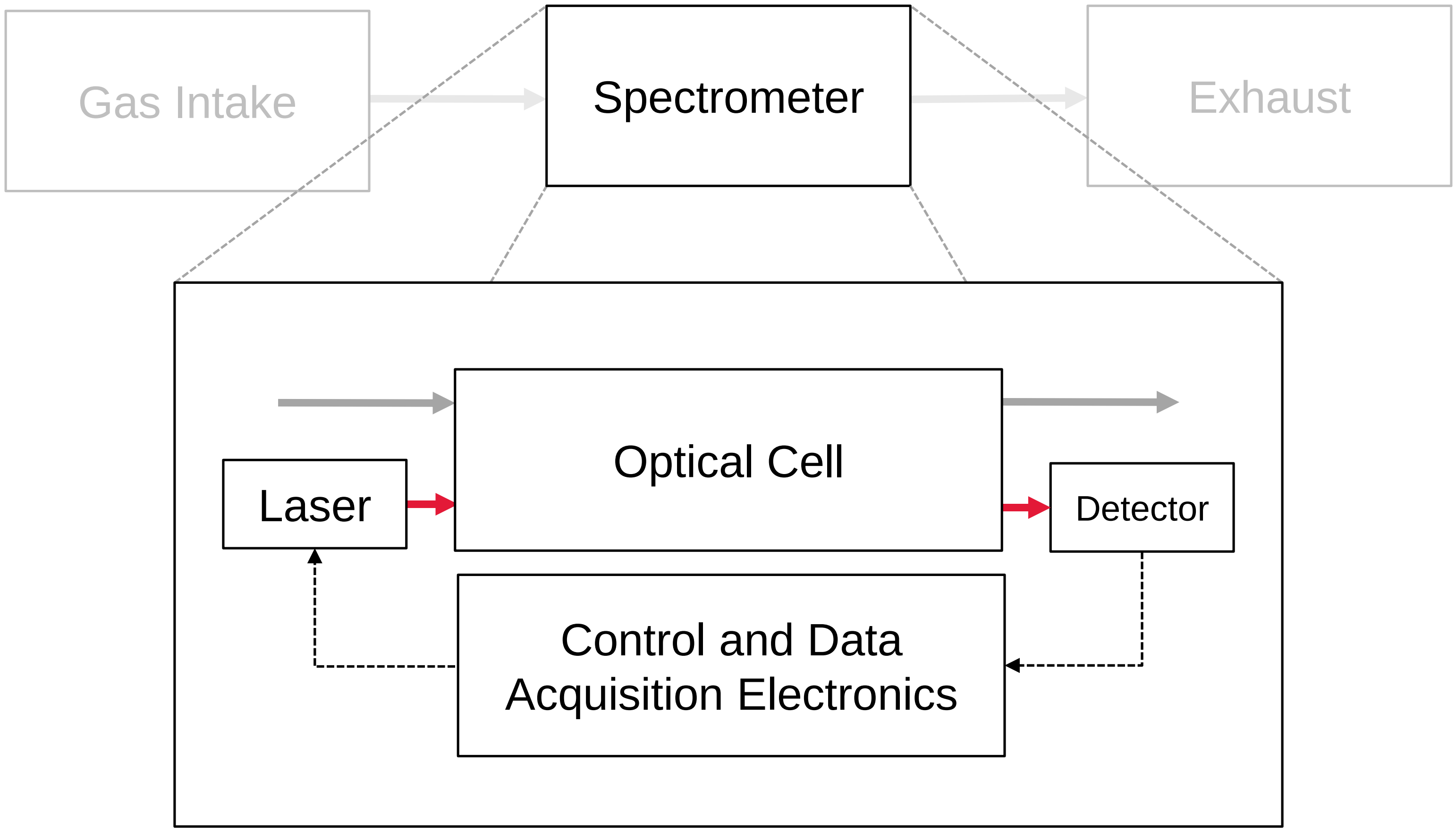
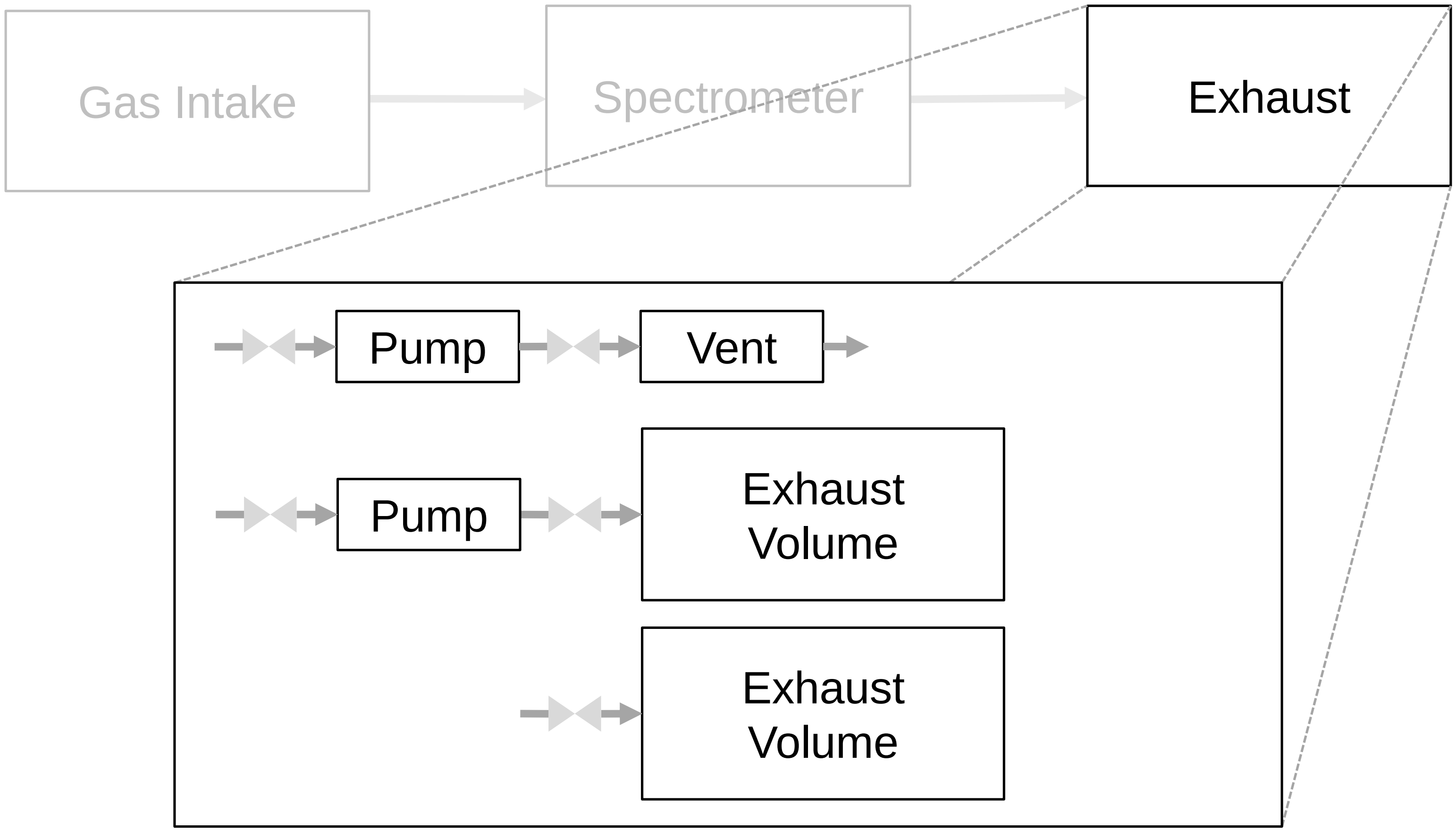
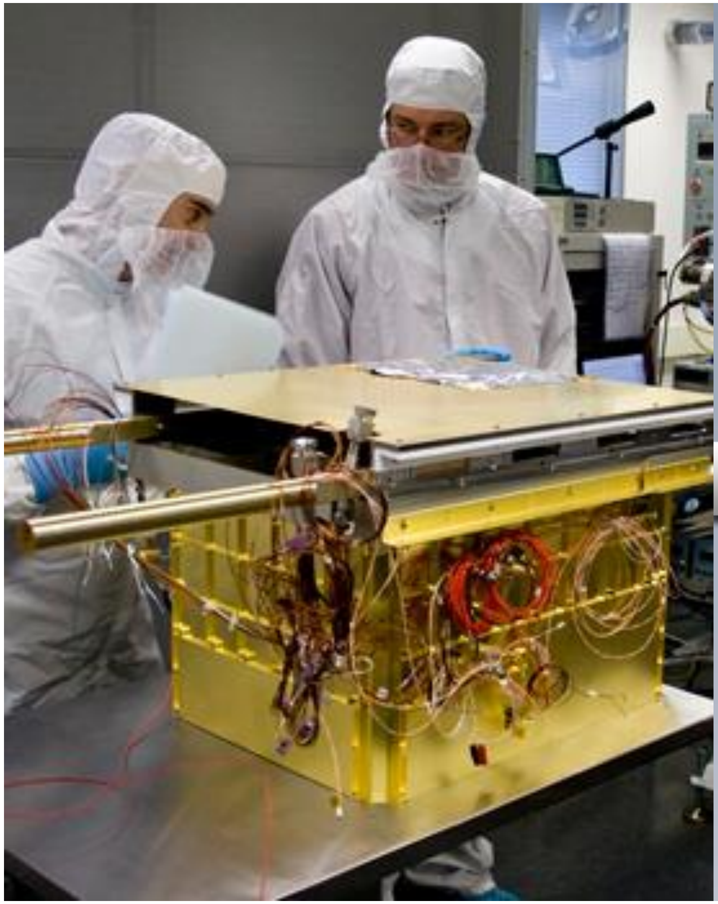
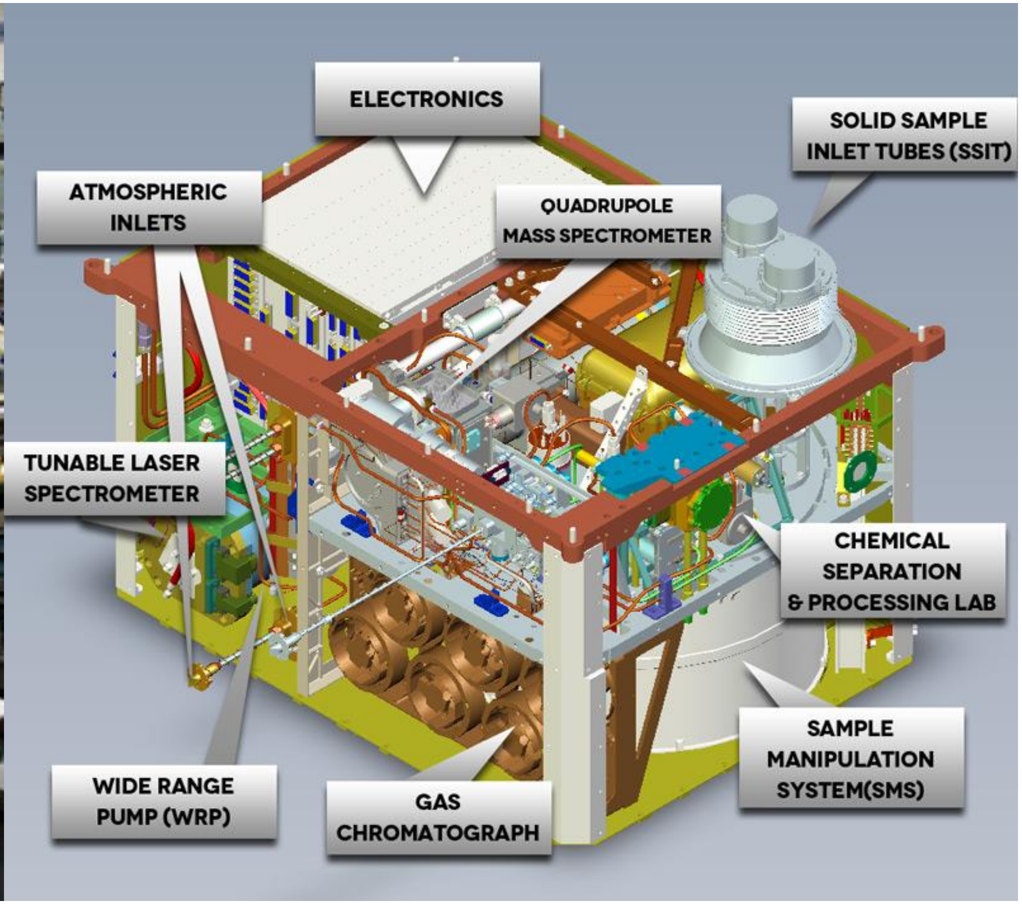


What does a TLS system look like?



Example: SAM suite on Curiosity





From SAM website: https://ssed.gsfc.nasa.gov/sam/samiam.html

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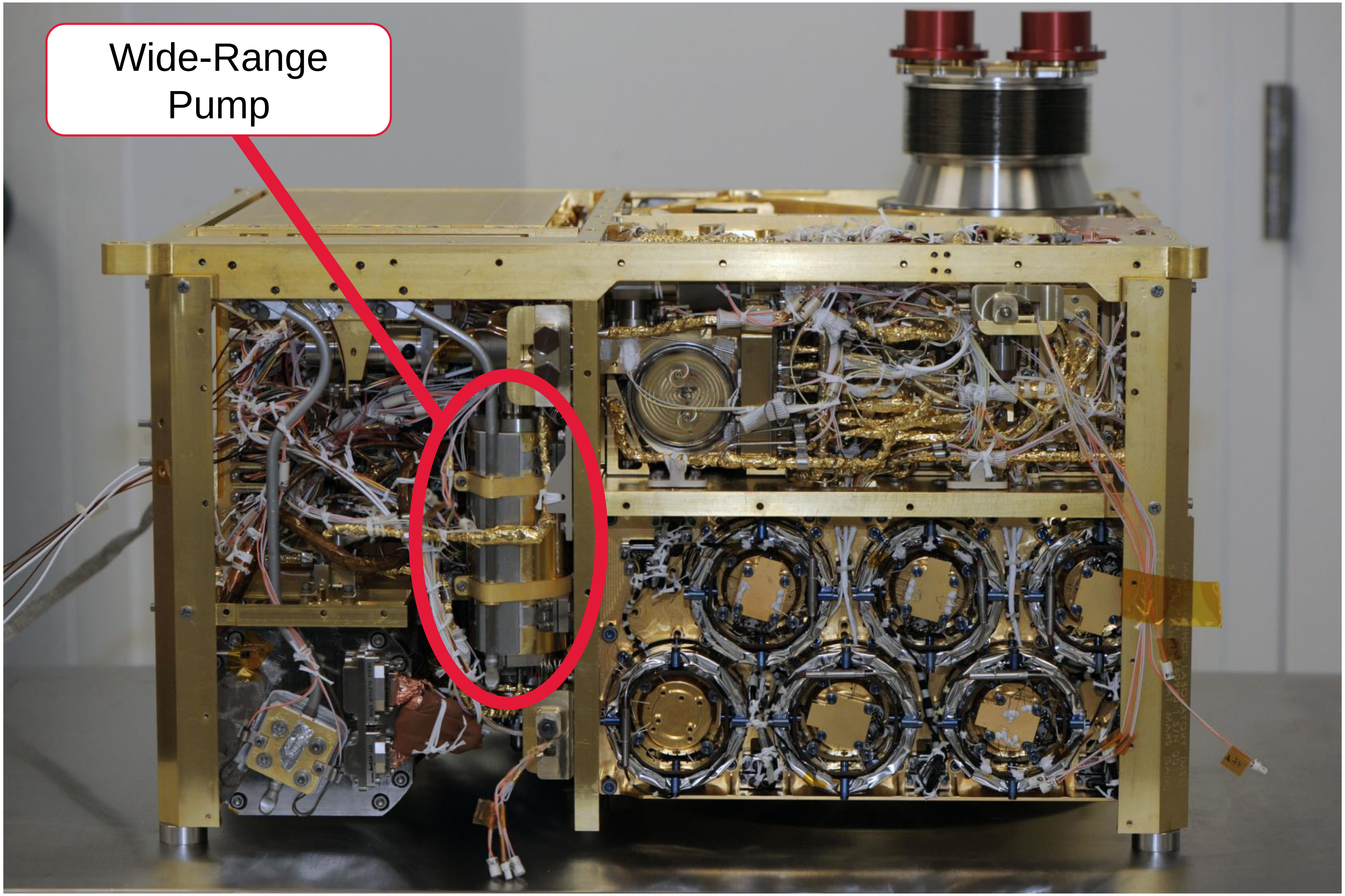

From MSL website: https://mars.jpl.nasa.gov/msl/multimedia/images/?imageid=4562

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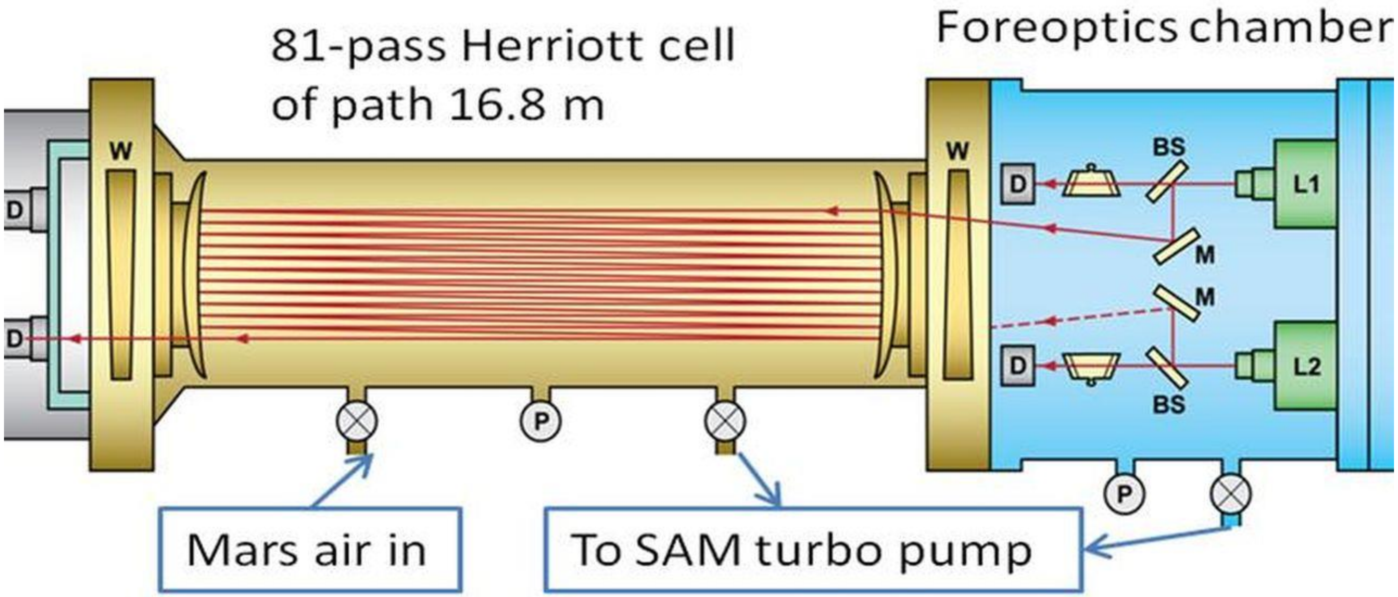
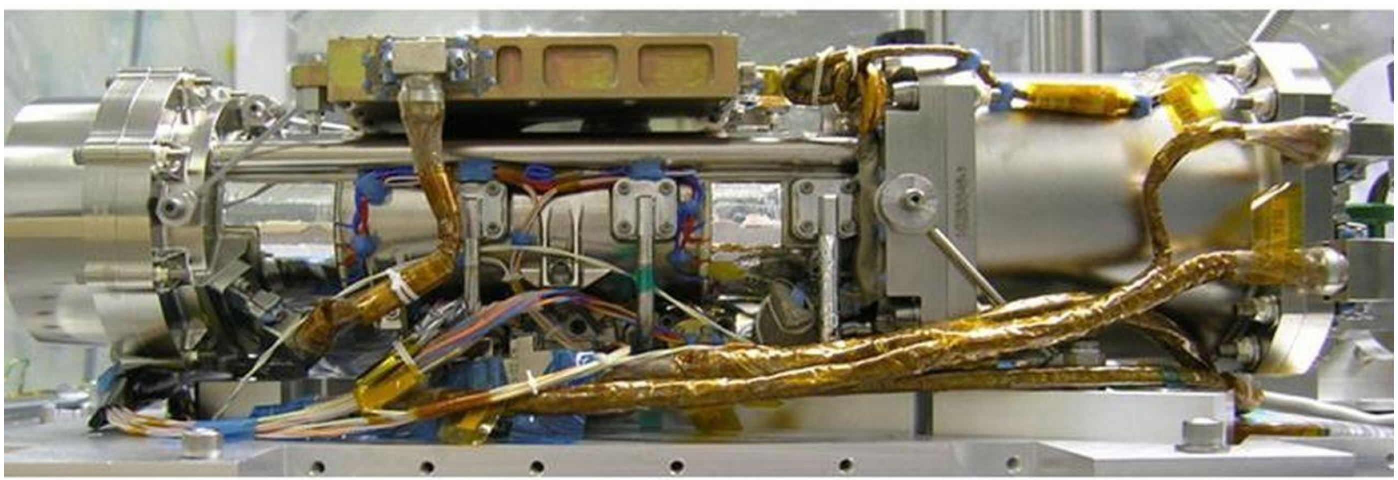




From JPL image gallery: https://www.jpl.nasa.gov/spaceimages/details.php?id=pia19086

What can we improve?

We can increase path length.

We can decrease noise.

We can decrease size / weight of instrument.

We can decrease sample volume / gas handling requirements.

What new science goals can we enable?

We can measure low-abundance targets without pre-concentration, such as methane on Mars or clumped isotopes.

We can measure difficult-to-collect samples, such as water vapor from comets or plumes on Enceladus.

We can operate in atmospheres containing difficult-to-pump balance gases, such as helium on Saturn.

Cavity Enhanced Spectroscopy

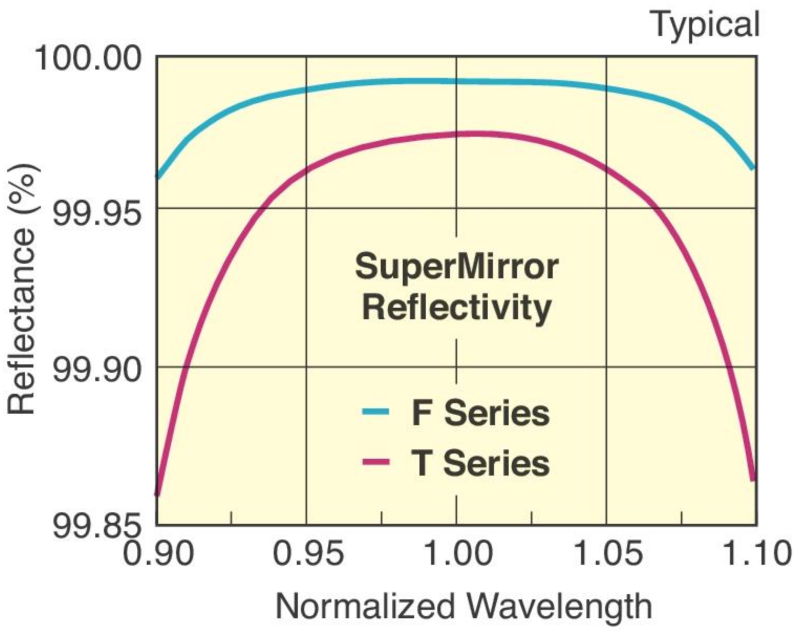
What is cavity-enhanced spectroscopy?

Cavity-enhanced spectroscopy uses an optical resonator to let light traverse the same path thousands of times, dramatically increasing path length.

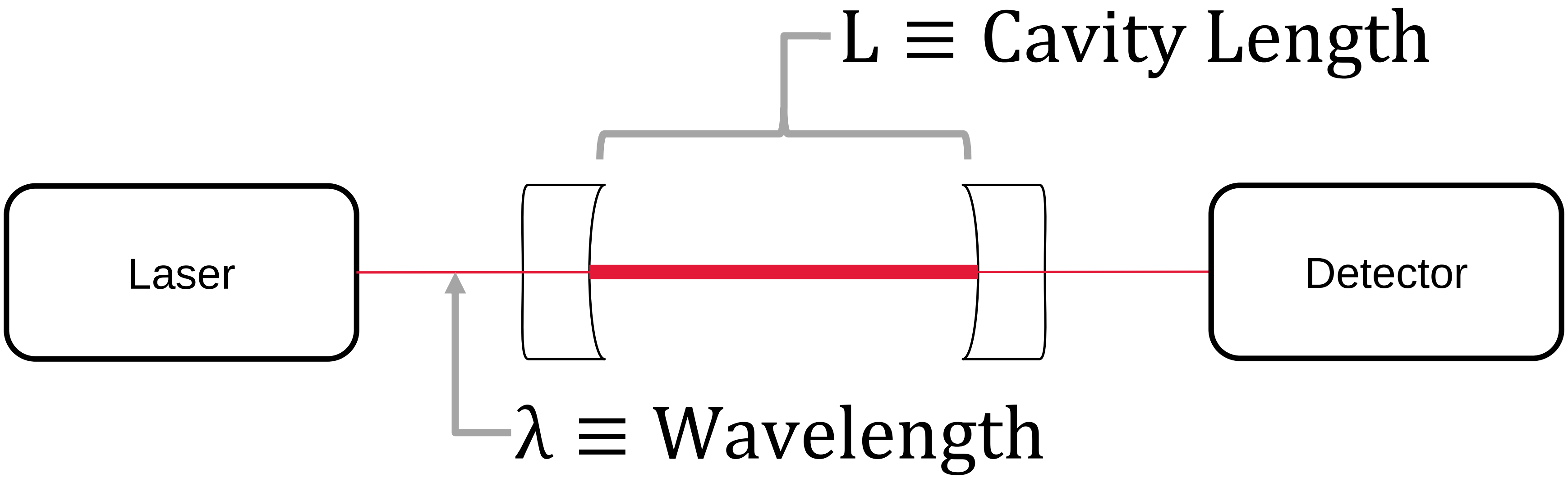
What is cavity-enhanced spectroscopy?

$$\mathbf{EPL} = \frac{\mathbf{L}}{\mathbf{1 - R}}$$

$$\frac{\mathbf{12\ cm}}{\mathbf{1 - 0.9998}} = \mathbf{600\ m}$$



Cavity resonance conditions

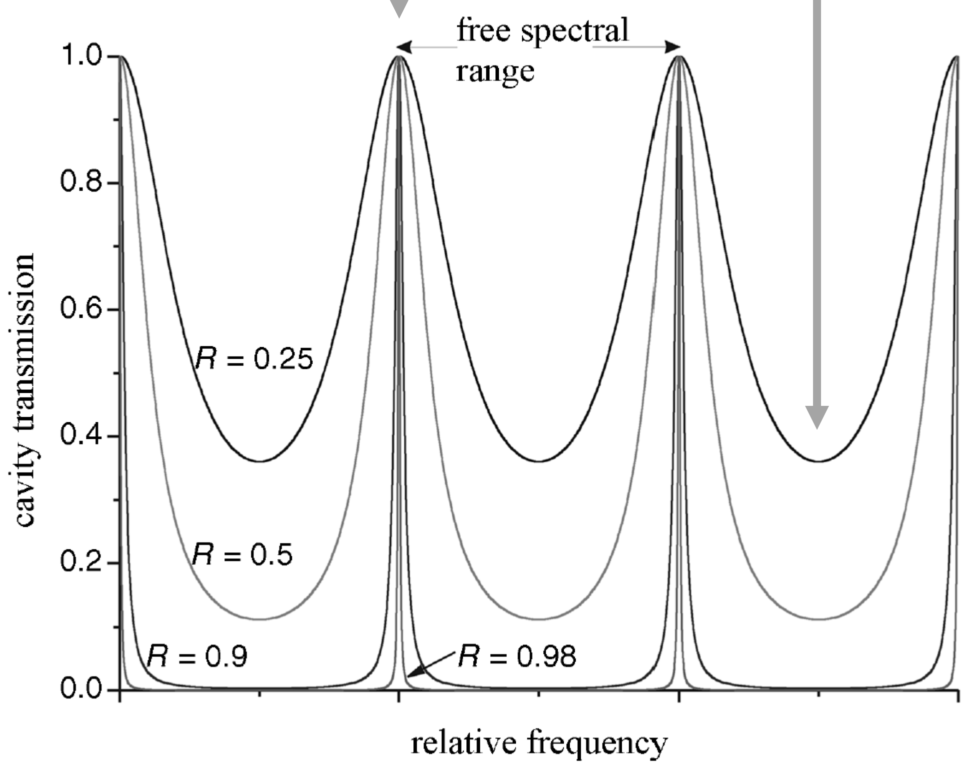


Resonance condition: $$\mathbf{L} = \frac{n\lambda}{2}$$

Cavity resonance conditions

$$\mathbf{L} = \frac{n\lambda}{2}$$

$$\mathbf{L} = \frac{n\lambda}{2} + \frac{\lambda}{4}$$



Plot from: Cavity Ring-Down Spectroscopy: Techniques and Applications, G Berden and R Engeln, 2009

What is cavity-enhanced spectroscopy?

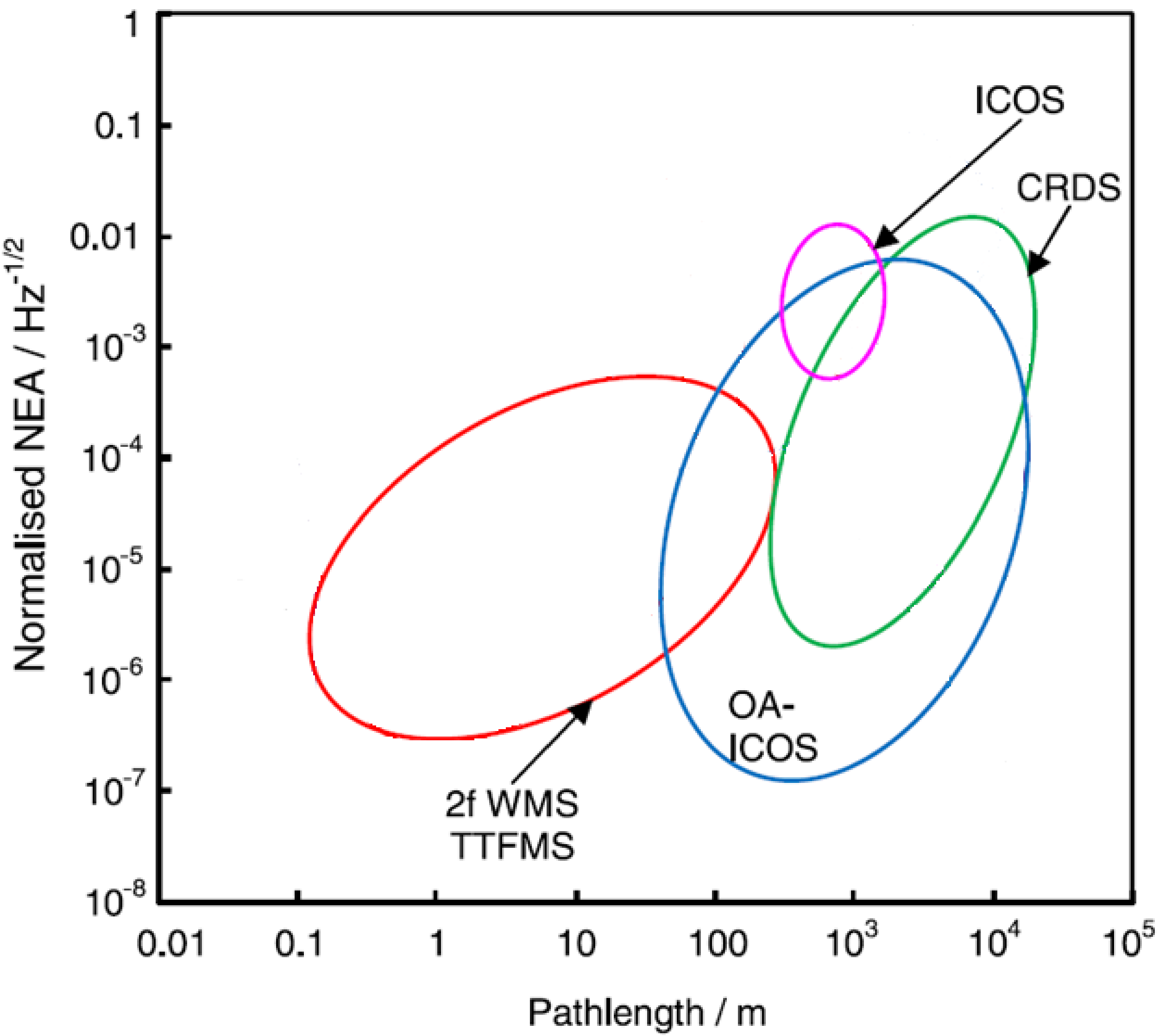
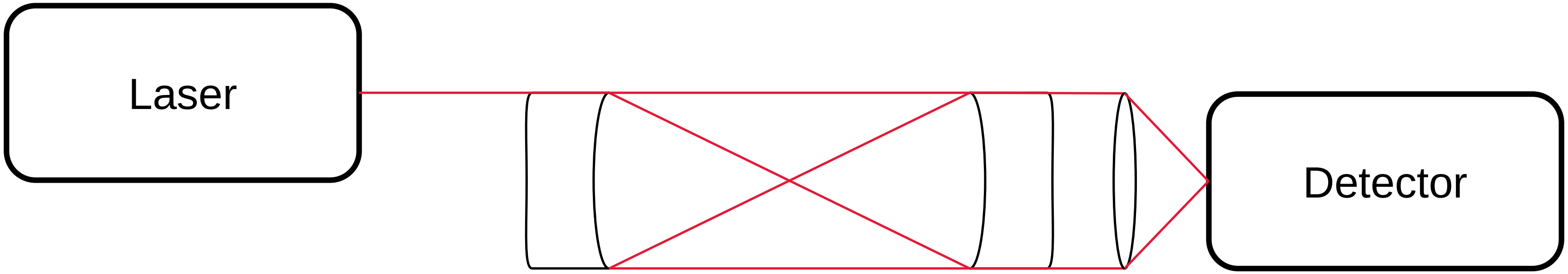


Figure adapted from J Hodgkinson and RP Tatam 2013 Meas. Sci. Technol. 24 012004

What is cavity-enhanced spectroscopy?

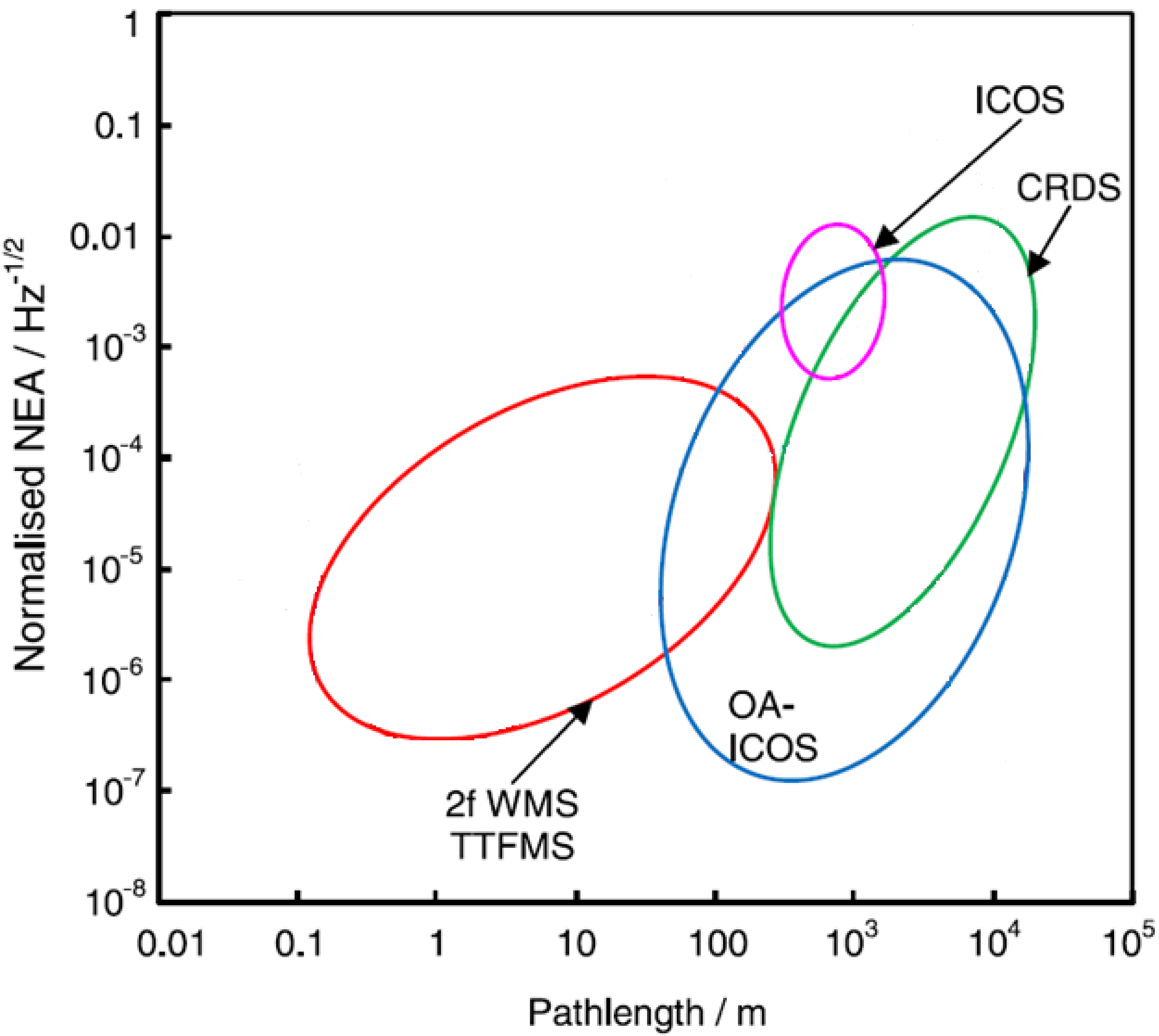


Off-Axis Injection:

Injecting light at an offset from the center of the mirrors increases distance traveled before beam overlaps (reentrance).

- Decreases FSR, noise from inconsistent coupling
- Does NOT increase EPL – still limited by mirror R
- Requires larger mirrors than axial configurations

What is cavity-enhanced spectroscopy?



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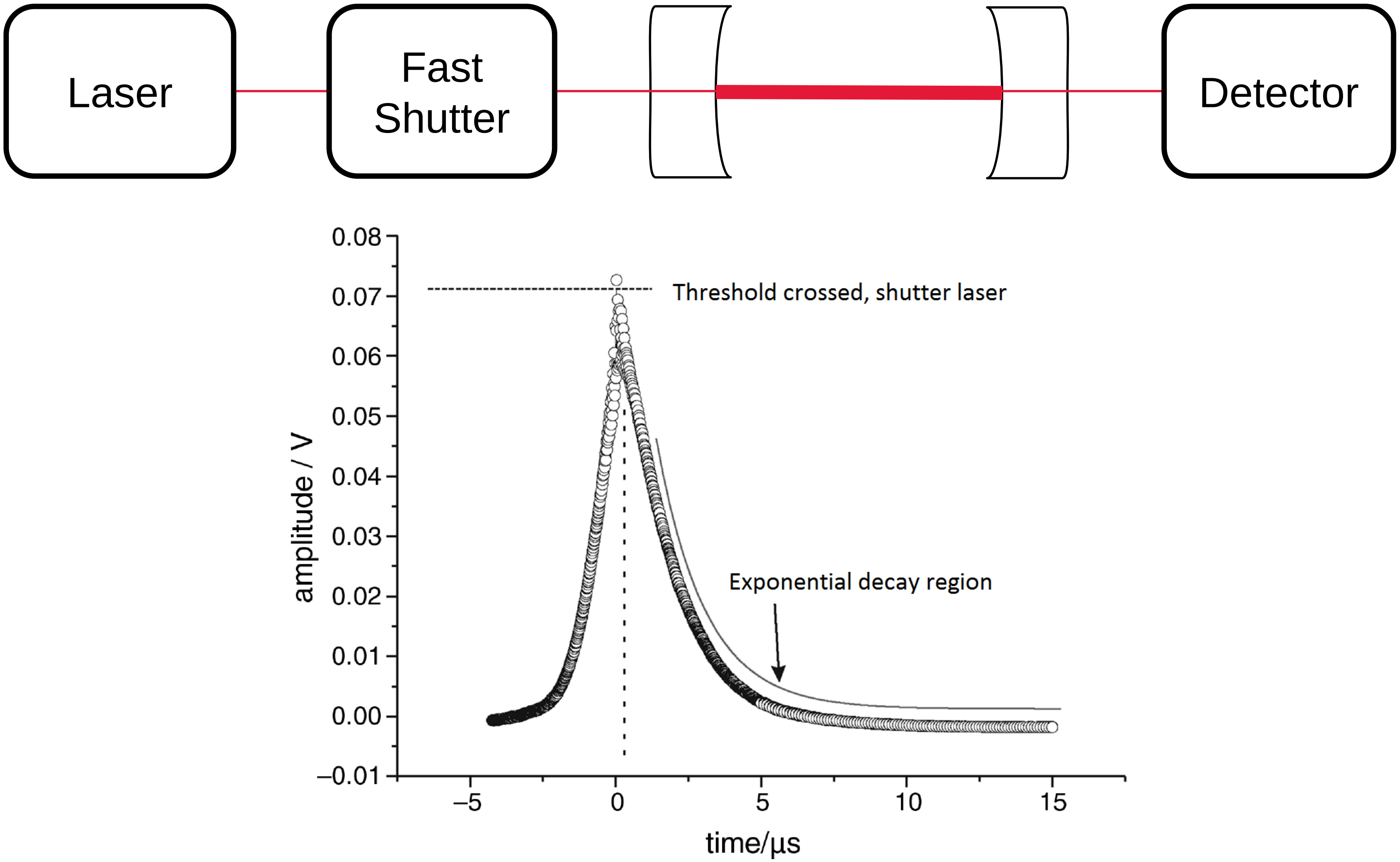
Alternate approach: Ringdown spectroscopy



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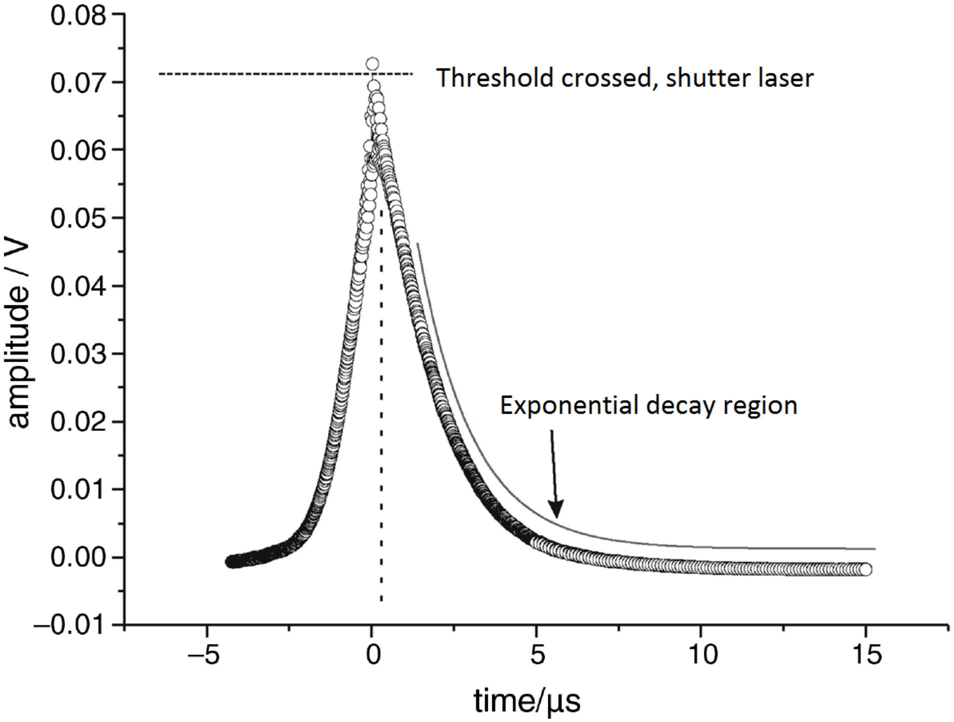


$$\tau_0 = \frac{nL}{c(1 - R)}$$

$$\tau = \frac{nL}{c(1 - R + \alpha L)}$$

$$\alpha = c\left(\frac{1}{\tau} - \frac{1}{\tau_0}\right)$$

Plot adapted from: Cavity Ring-Down Spectroscopy: Techniques and Applications, G Berden and R Engeln, 2009

Comparison of CEAS techniques

NICE-OHMS

- Best laboratory performance, not field-ready

OA-ICOS

- Good laboratory performance, best field performance
- Large mirrors → large sample volume
- Significant performance loss if cavity is shortened

CRDS

- Best laboratory performance, good field performance
- Small mirrors → small sample volume
- Can be short (10 cm), but needs piezo actuators to account for large FSR

Design tradeoffs: Mirror reflectivity

- Higher reflectivity mirrors give longer effective path length, but make coupling more challenging

- Available reflectivity varies by wavelength – best at telecom bands (>99.999%), worst in UV / thermal IR (>99.97%)

$$\frac{\mathbf{12\ cm}}{\mathbf{1-0.9997}} = \mathbf{400\ m}$$

$$\frac{\mathbf{12\ cm}}{\mathbf{1-0.99999}} = \mathbf{12,000\ m}$$

Design tradeoffs: Cavity length

- Challenging to measure $\tau < 1\ \mu s$; for 99.97% mirrors, minimum cavity length ≈ 10 cm
- Longer cavity more sensitive, but larger volume and may be difficult to fit in small spacecraft
- Longer cavity gives better FSR – could do without piezos in a large instrument, not practical for compact instruments

Design tradeoffs: Triggering method

Acousto-optic modulator:

- Fast response, does not perturb laser
- High power, water cooled

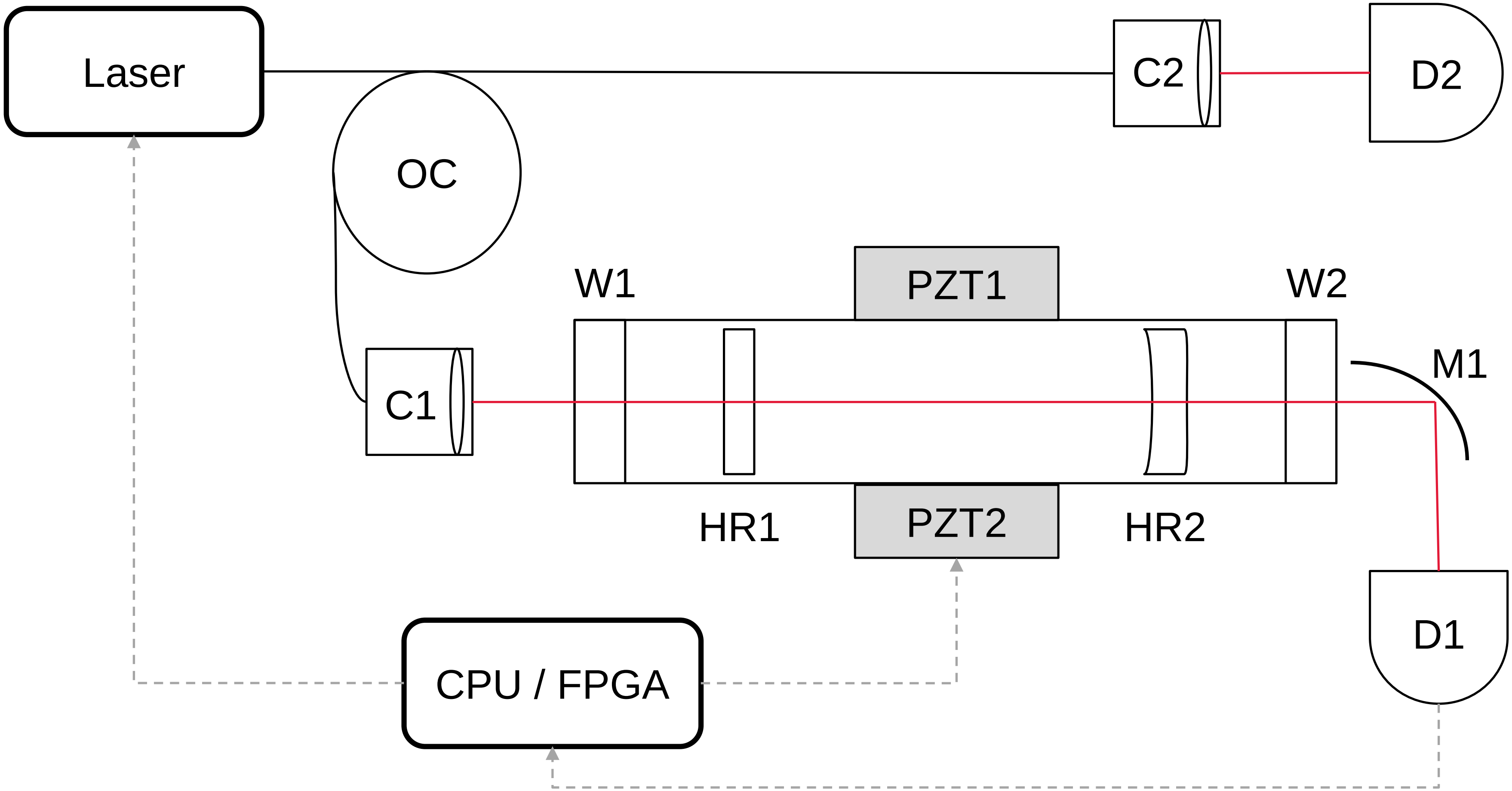
Semiconductor optical amplifier:

- Fast response, does not perturb laser
- Limited wavelength availability

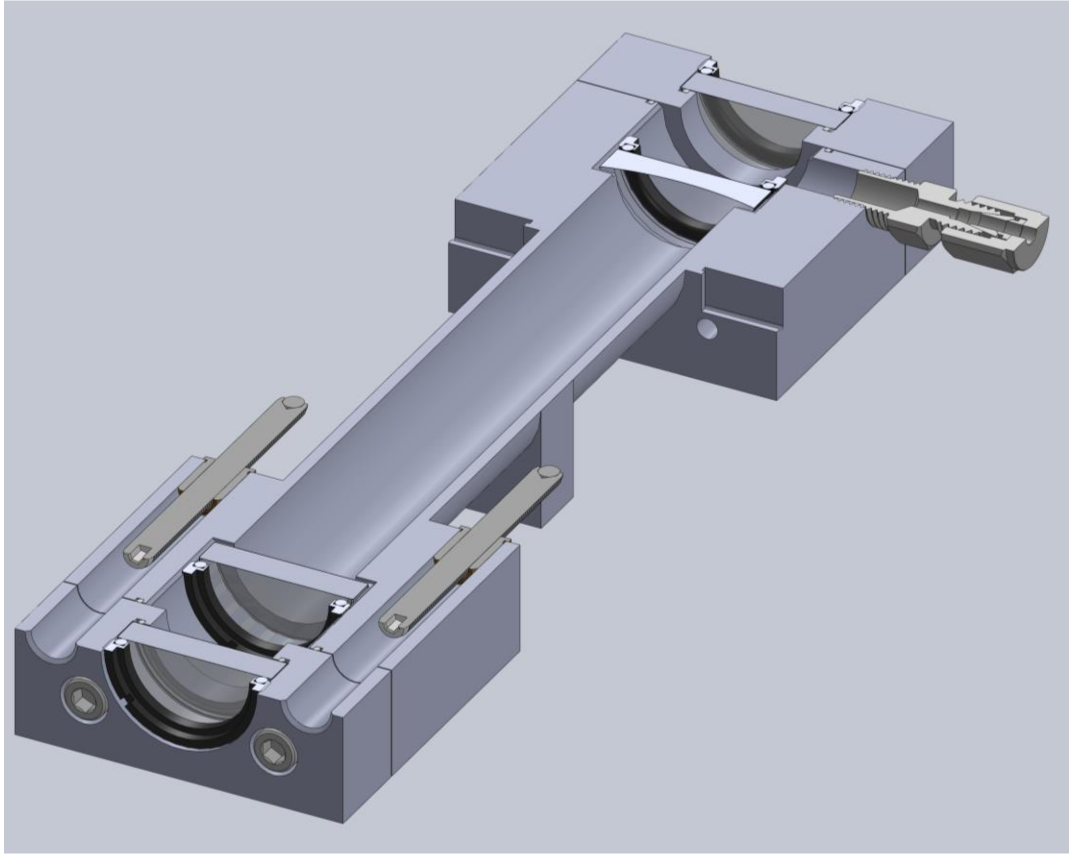
Laser current modulation:

- Slower response, laser requires re-stabilization period
- No extra equipment, available for all semiconductor lasers

Prototype Water Analyzer Overview

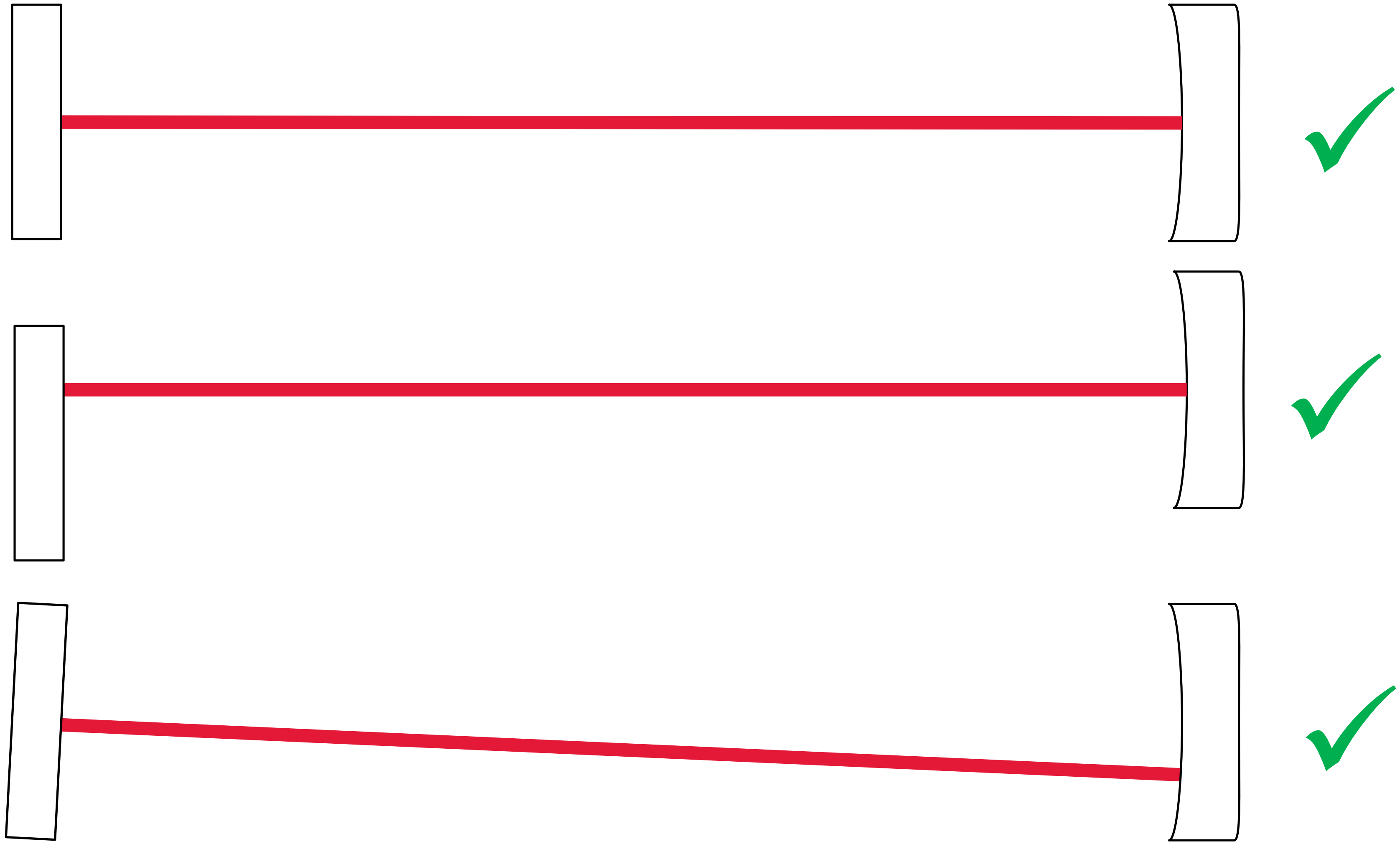


Cell design



- 12 cm mirror separation
- 630 m EPL
- Mirrors masked to 5mm ø
- 2.35 cc probed volume

Cell design: Plano-concave cavity



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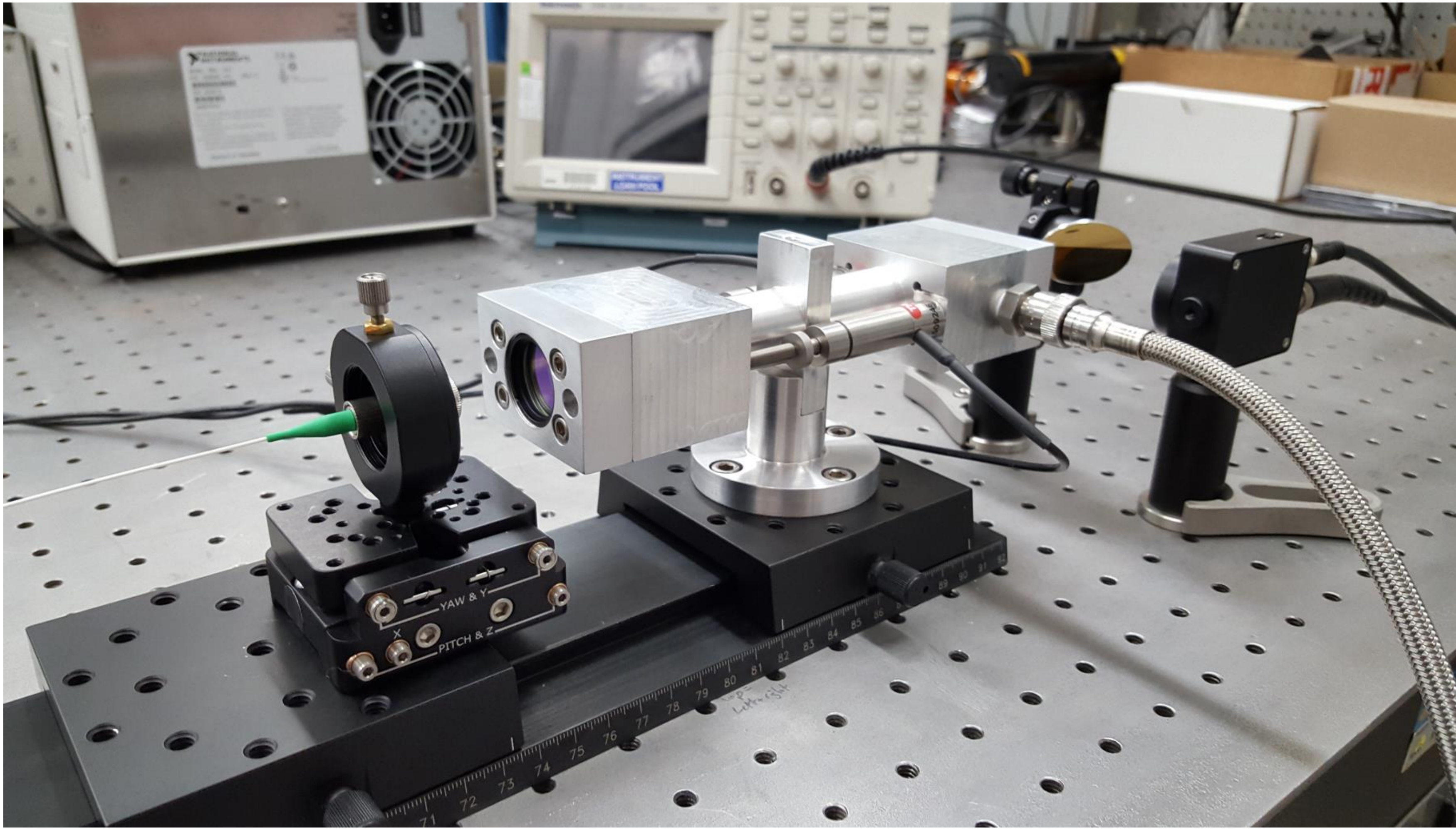


FPGA system

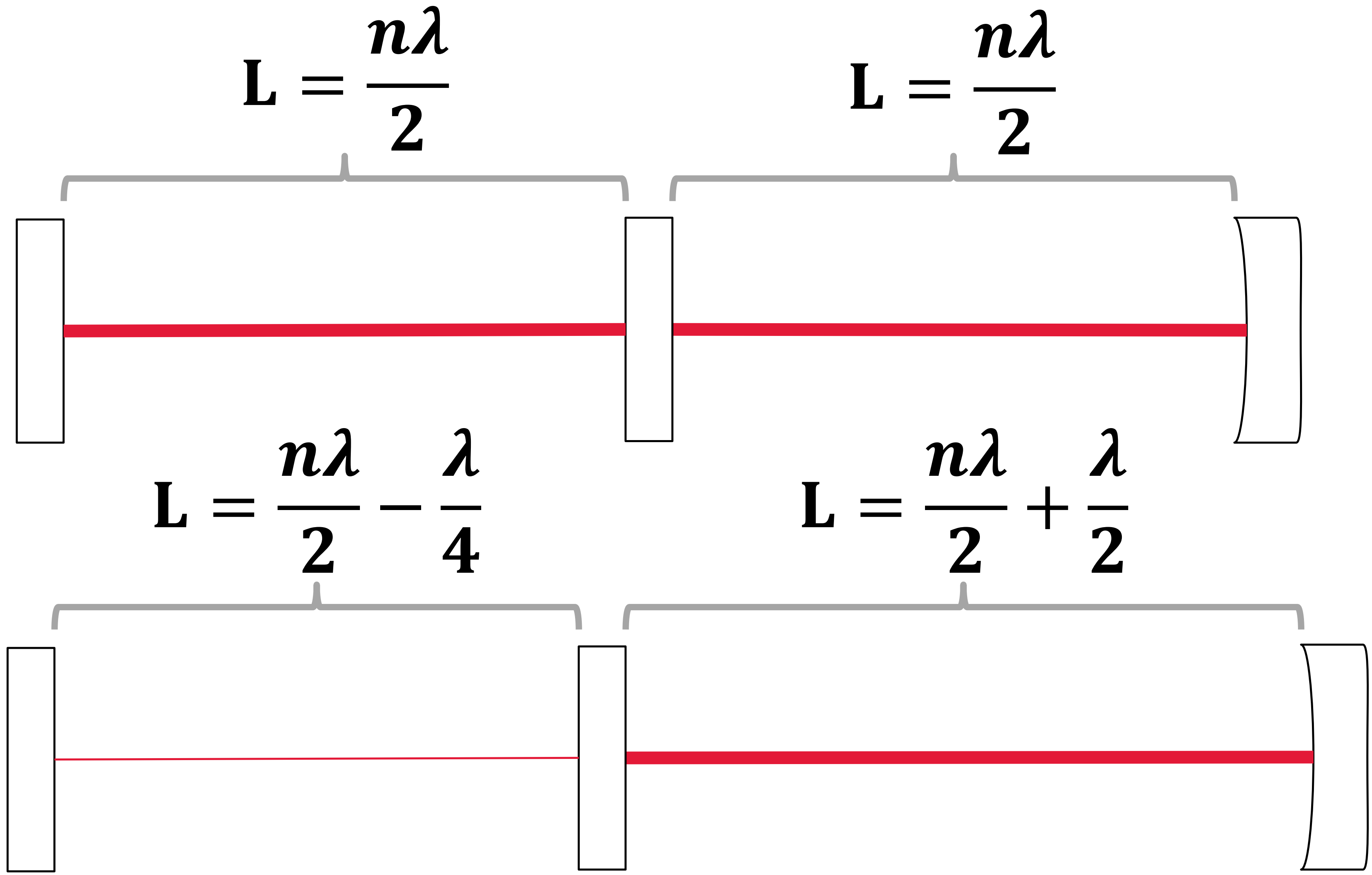
FPGA

- Modulates laser
- Modulates piezo
- Interfaces with ADC
- Detects & triggers RDs
- Records RDs & metadata
- Passes data to CPU

CPU

- Sets laser scan parameters
- “Locks” piezo range
- Fits RDs to exponential function
- Controls fringe cancellation system
- Writes spectrum & metadata to file

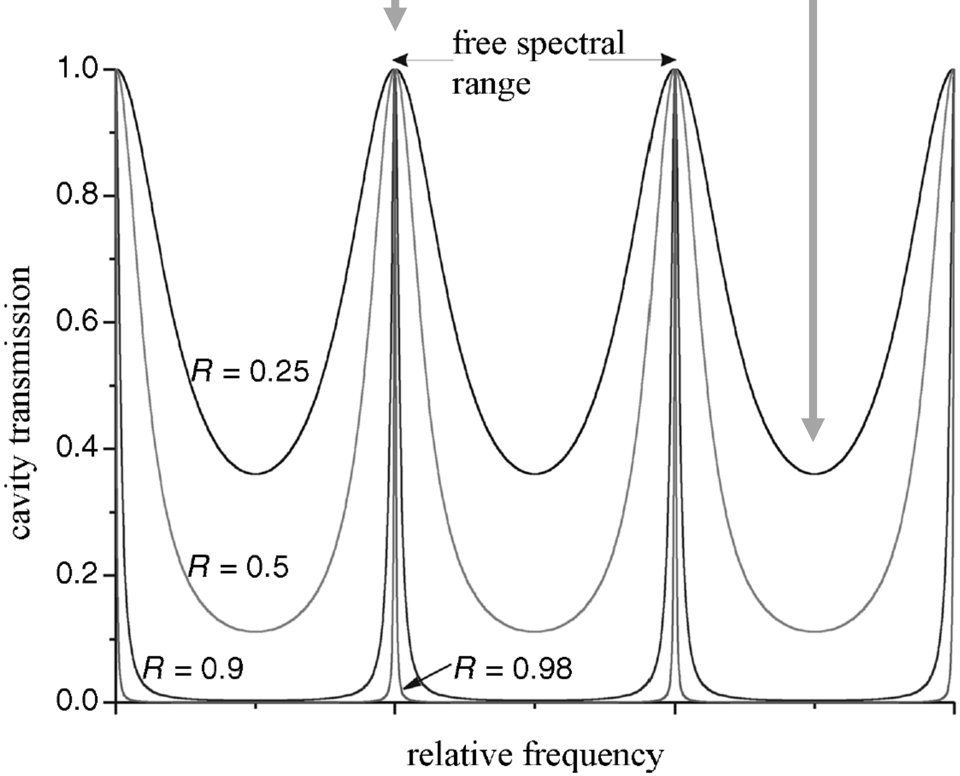
Fringe cancellation



Fringe cancellation

$$\mathbf{L} = \frac{n\lambda}{2}$$

$$\mathbf{L} = \frac{n\lambda}{2} + \frac{\lambda}{4}$$



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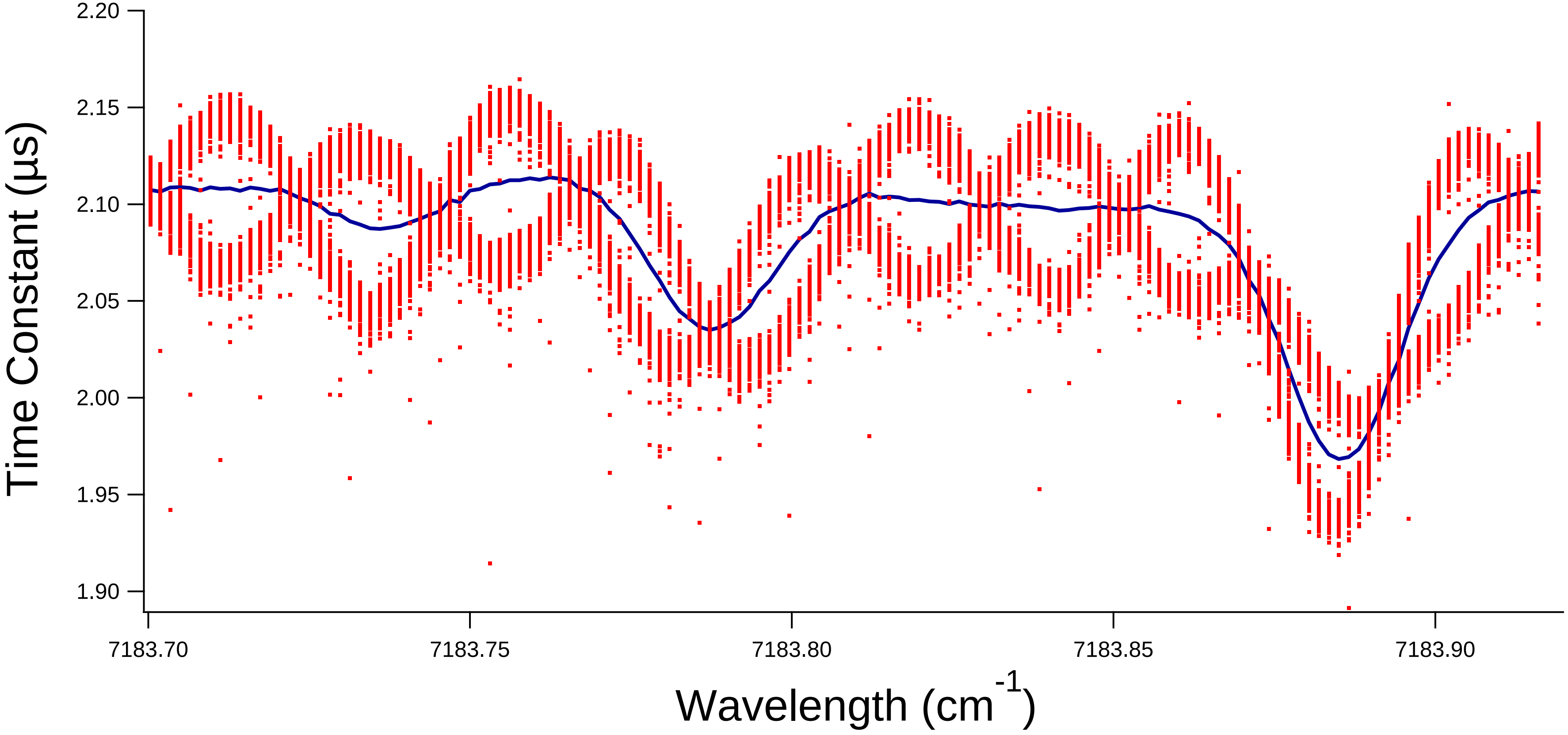
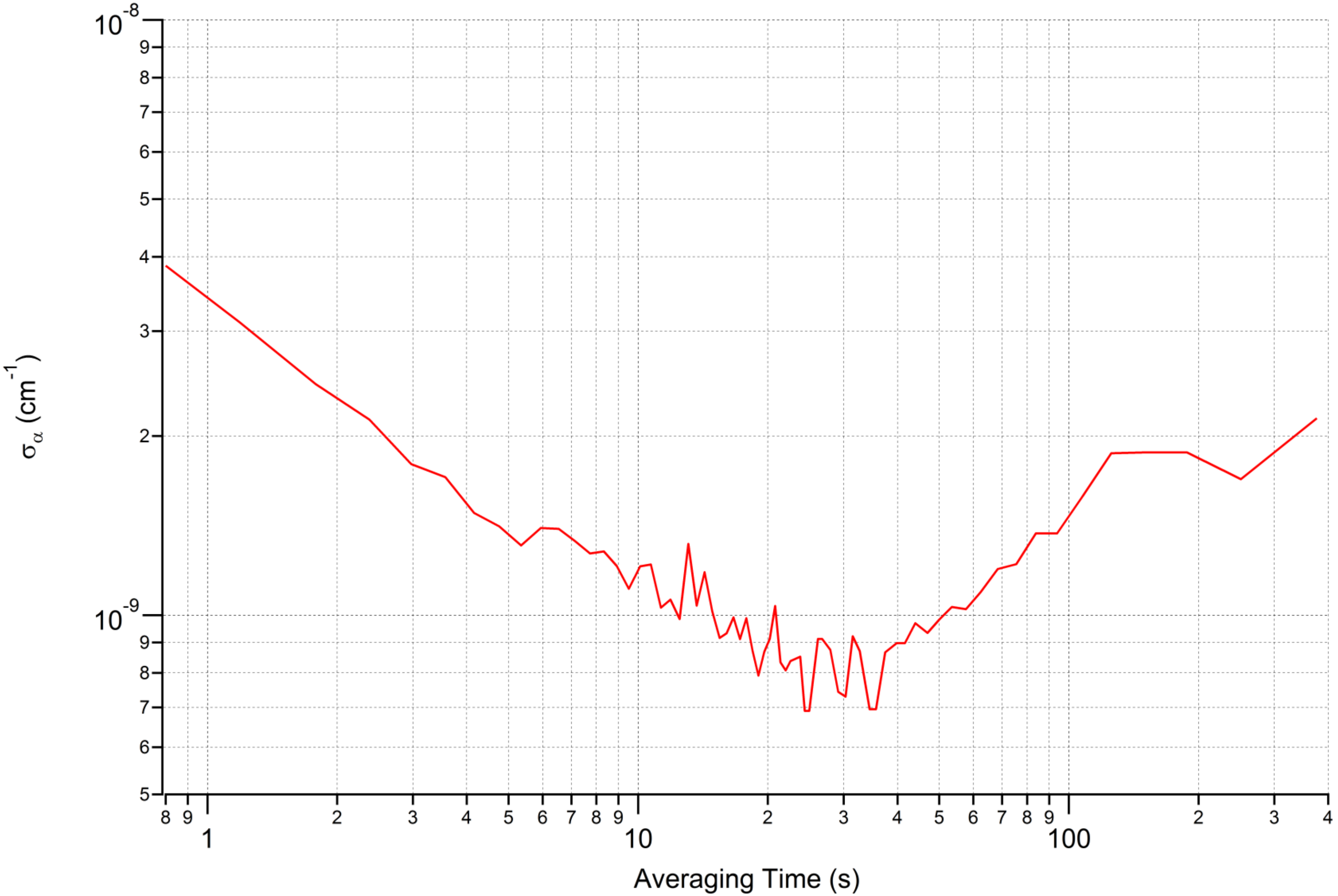


Spectrometer performance



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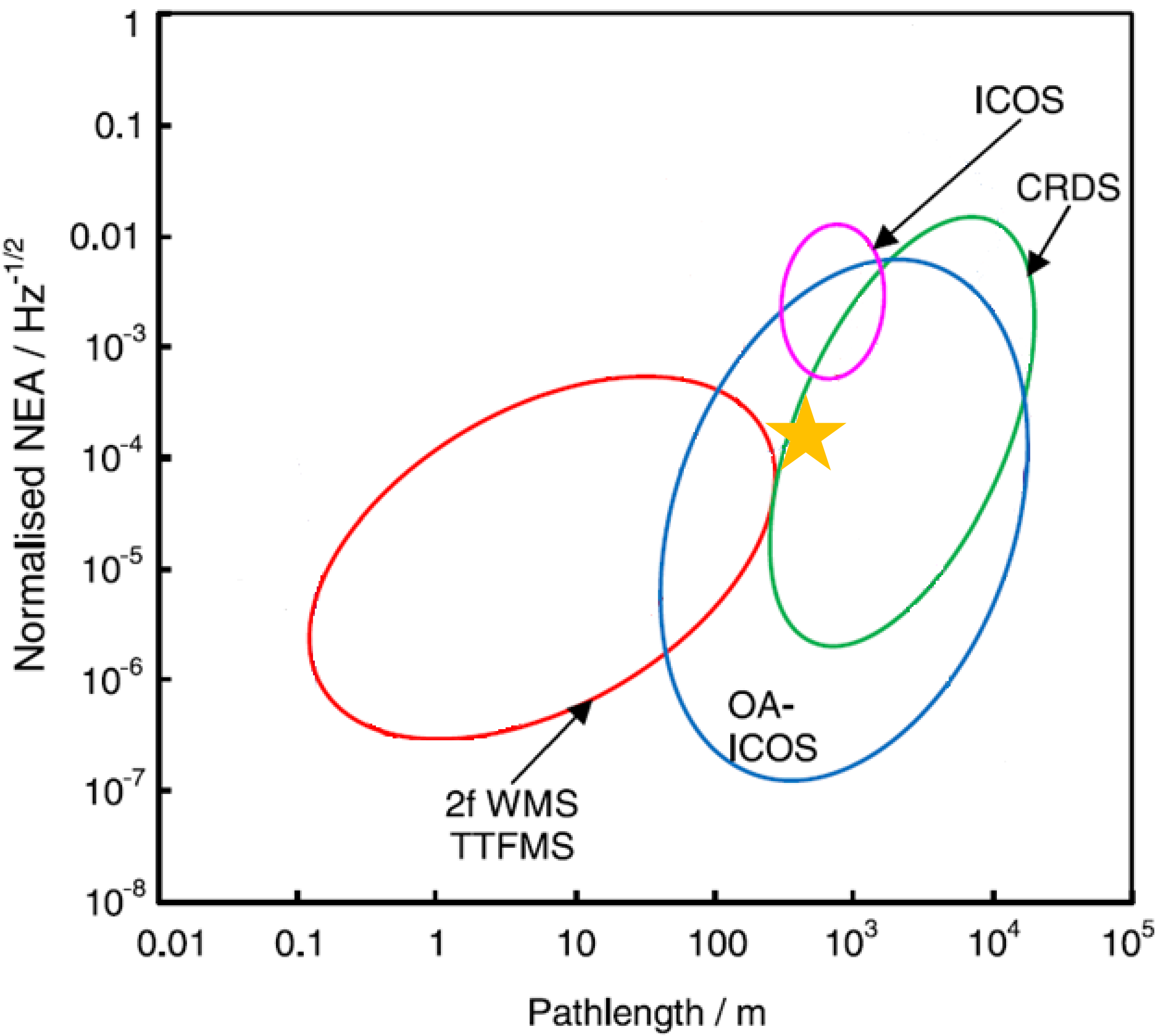

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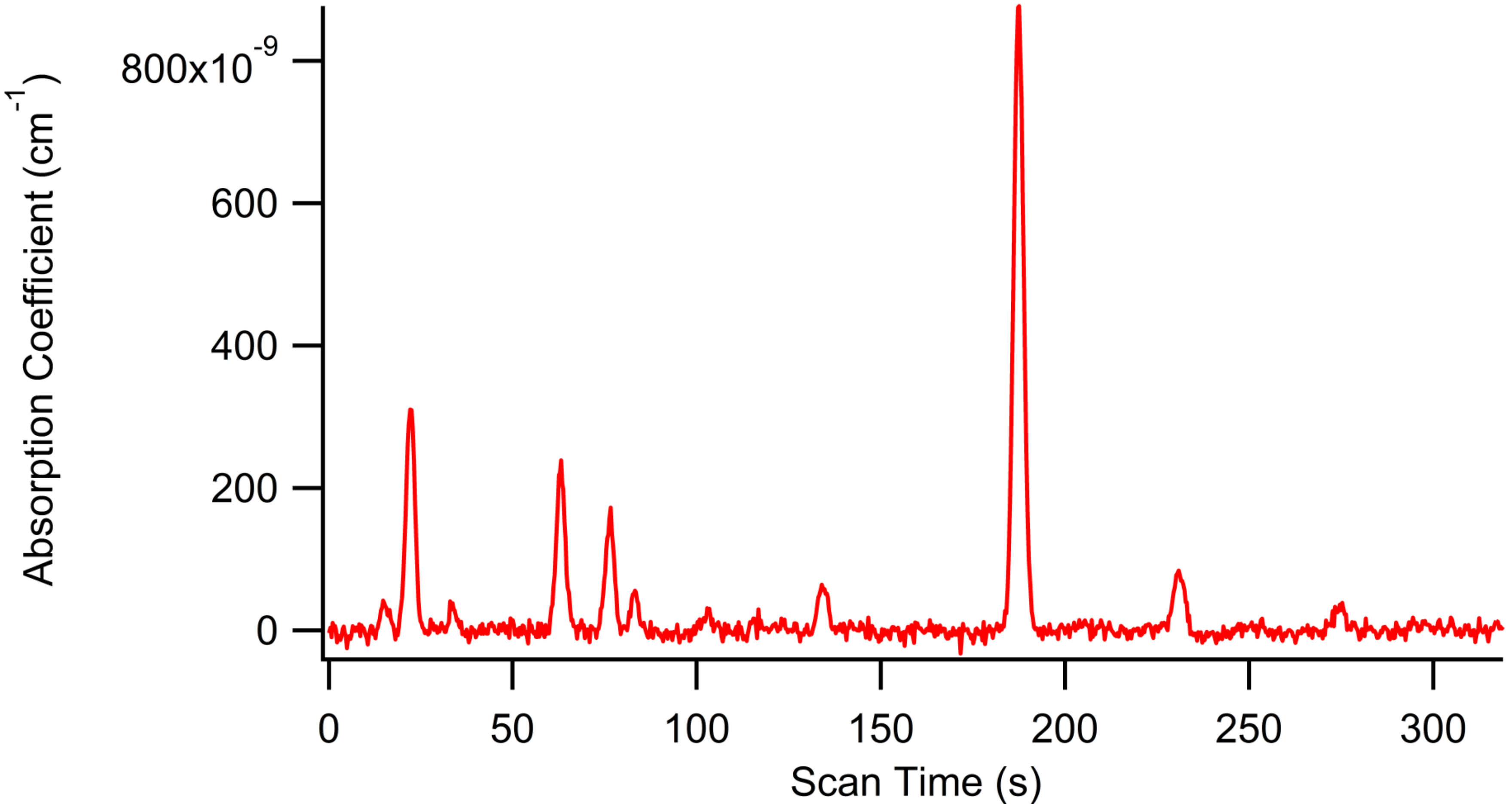

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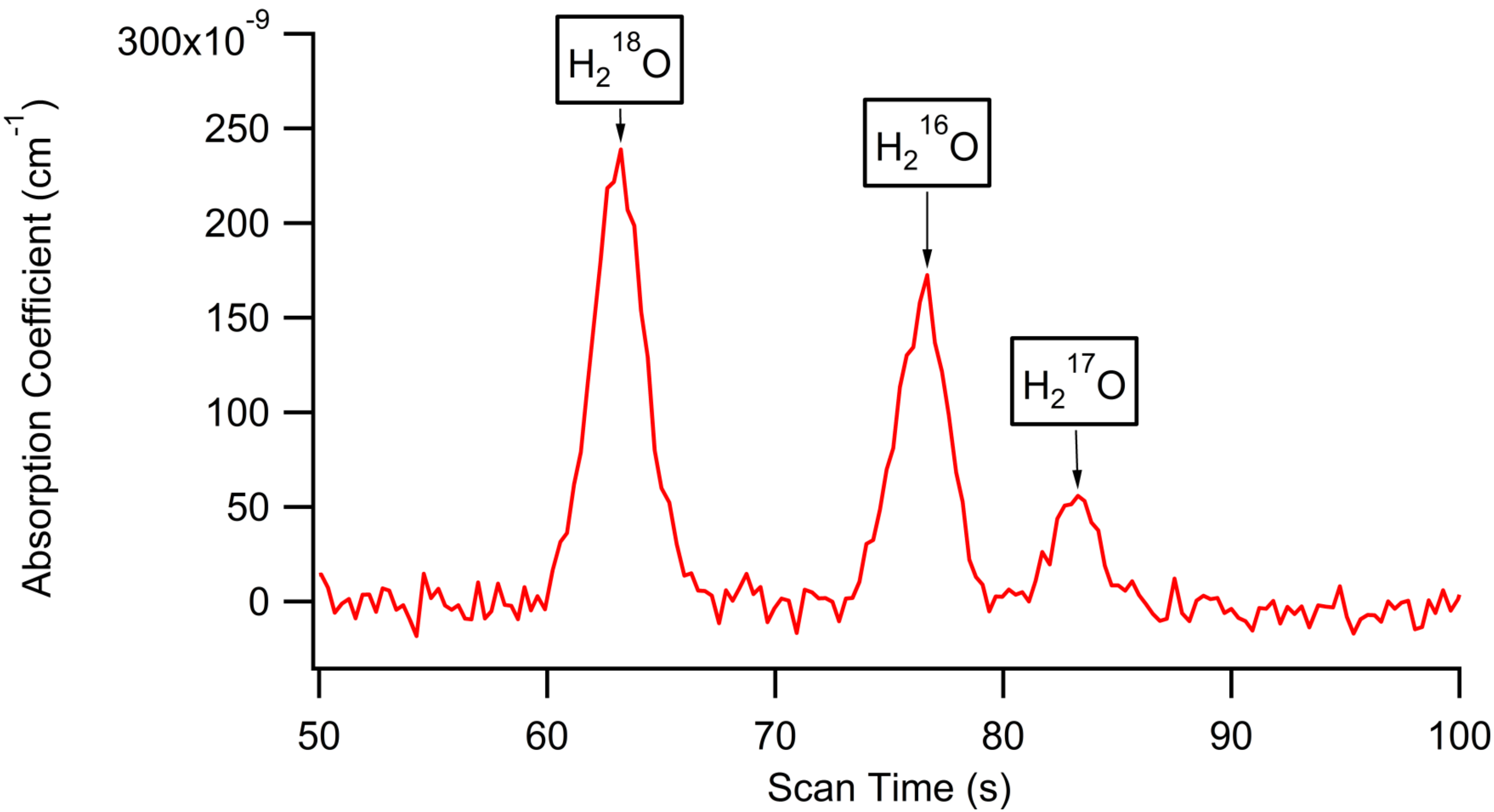

Spectrometer performance

Scan Parameter	Value
Cell Pressure	1 mbar
H_2O Partial Pressure	45 µbar
Temperature	~294 K
Scan Time	50 s
Laser Power	10 mW

Isotope Ratio	Precision (‰, 1σ)
δ18O	±0.024
δ17O	±0.11

What can we improve in the future?

- Demonstrate performance at other wavelengths
  - Currently working on methane measurements at 3.27μm
- Demonstrate reliability in field settings – UAV measurements
  - Need to design and build second-generation cell, miniaturized electronics
- Find source for semiconductor optical amplifiers at non-telecom wavelengths

Acknowledgements

Mini-TLS Team:

- Chris Webster
- Jordana Blacksberg
- Didier Keymeulen
- Greg Flesch
- Erik Alerstam

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California Institute of Technology